Alternating-current Armature Windings

THEORY, PRACTICE, AND DESIGN

Other Titles
by
CHARLES S. SISKIND

Electricity—Principles, Practice, Experiments
Direct-current Armature Windings—Theory and Practice
Electrical Machines—Direct and Alternating Current

Alternating-current Armature Windings

THEORY, PRACTICE, AND DESIGN

BY

CHARLES S. SISKIND, M.S.E.E.

Assistant Professor of Electrical Engineering
Purdue University

NEW YORK TORONTO LONDON

McGRAW-HILL BOOK COMPANY, INC.

1951

ALTERNATING-CURRENT ARMATURE WINDINGS

THEORY, PRACTICE, AND DESIGN

Preface

The material in this book—a companion volume to "Direct-current Armature Windings"—is a carefully planned simplification of the principles and present-day practices of alternating-current armature windings. The detailed treatment of the various types of windings, and their applications to single-phase and polyphase machines, is essentially similar to the author's teaching procedure used in his courses in a-c machinery.

Considerable emphasis has been placed upon elementary principles and the relation between fundamental winding arrangements and their modern practical counterparts. In the discussion of the various types of construction, an attempt has been made to avoid gaps between ideas that are simple and easily understood and those which, because they are variations and combinations of basic types and connections, are apparently more complex. Numerous examples are given to illustrate important ideas, and these are generally supplemented by appropriate clear-cut sketches and photographs. The winding diagrams, representing as they do an important link between descriptive explanations and physical constructions and arrangements, have received very special attention; these are chosen, for the most part, from actual practical experience and are drawn simply, clearly, and to a scale that is easily traced.

Single-phase windings—*spiral*, *concentric*, and *skein* types—are considered first, in connection with their use in repulsion and split-phase motors. The subject next develops rather naturally to a study of the *concentric-chain* polyphase winding, which is, in fact, a variation of the type common to single-phase machines. Polyphase wave and lap windings are then taken up in succession to complete the important list of modern winding types.

Multispeed windings for single-phase and polyphase motors are discussed in considerable detail and are treated in a manner that is both original and easy to follow; the student should find this branch of the subject particularly worth while since it indicates the extent to which fundamental winding arrangements are modified to extend the possibilities of motor operation. Still another topic that is given rigorous treatment, again from a uniquely original point of view, is the *fractional-slot lap* winding; an entirely new method of laying out such a winding is presented in Chap. 13.

The book is a thoroughly practical analysis of a subject that, far from being complex and difficult, is easy to master when studied carefully and systematically. Moreover, since the armature winding is the very heart of the a-c machine, it is felt that a familiarity with its principles and practices is essential to an understanding of alternator and motor performance. Practical shop winders and others engaged in the operation of electrical machines should find the material particularly worth while; it should also be useful to those desirous of improving themselves by home study. In formal electrical courses the book will be found especially adaptable to trade, vocational, and engineering schools and as a supplementary text for students of a-c machinery.

CHARLES S. SISKIND

WEST LAFAYETTE, INDIANA
May, 1951

Contents

CHAPTER 1

General Comparisons between D-c and A-c Armature Windings

Before undertaking the detailed study of alternating-current armature windings, it will be desirable, in this introductory chapter, to make a number of generalizations concerning important similarities and differences between windings used in d-c and a-c machines. Such comparisons should prove extremely helpful to the student, assuming, of course, that he is familiar with the principles of d-c armature windings.*

The Armature Winding and the Magnetic Field

The primary function of every current-carrying armature winding is to create magnetism. To accomplish this most effectively, the copper coils, constituting the armature winding, must be arranged in definite symmetrical patterns in the slots of the armature core and joined together in accordance with well-established practices.

In the modern d-c armature, which always rotates, the flux it creates is stationary in space. On the other hand, the magnetic field rotates in the usual polyphase a-c generator or motor where the armature winding is stationary. Note that the two types of machine differ from each other structurally, in that the armature winding rotates in one and is stationary in the other; however, they do function similarly, because in both types there is *relative motion* between the armature winding and its created magnetic field.

In some special types of polyphase a-c motor, and in the *rotary converter*, a magnetic field that is stationary in space is created by a rotating armature winding. The split-phase single-phase a-c motor functions in still another way, namely: (1) During the starting period two stationary armature windings create a revolving magnetic field; and (2) after the rotor has reached normal speed, one of the stationary armature windings is disconnected from service, at which time the specially constructed squirrel-cage rotor aids the single-stator winding in maintaining a revolving magnetic field.

* Siskind, C. S., "Direct-current Armature Windings," McGraw-Hill Book Company, Inc.

The foregoing discussion, therefore, leads to the general statement that **in any d-c or a-c machine there is always relative motion between the armature winding (or windings) and its created magnetic field.** It is well to remember this very important fact, especially in the study of a-c windings, because it is helpful in understanding why armature coils are arranged and interconnected in the manner described in subsequent chapters.

Closed-circuit and Open-circuit Windings

All d-c armature windings are *closed-circuit* windings; for this reason they are said to be *reentrant.* In simplex or in multiplex singly-reentrant

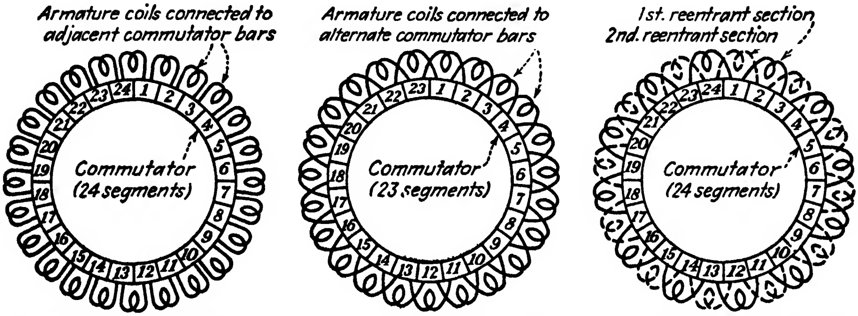


FIG. 1. Sketches indicating that d-c windings are *closed-circuit* windings. (Lap windings are illustrated for simplicity.)

d-c windings, for example, all the coils are joined together in symmetrical succession at the commutator, so that tracing all the coils from any point always results in a return to the starting point. In multiplex doubly-reentrant, triply-reentrant, or, in general, multiple-reentrant d-c windings, tracing always results in two, three, or multiple *complete* closures. This is illustrated schematically in Fig. 1 for simplex, for duplex singly-reentrant, and for duplex doubly-reentrant windings.

All a-c armature windings are *open-circuit* windings. This implies that the ends of each phase of a two- or three-phase winding (or the complete winding in the case of single-phase machines) are, in effect, connected to the source of supply for motors or to the load for alternators. In other words, each phase of a given armature winding is closed by means of something external to it; for alternators this means the electrical load; and for motors, the corresponding windings of the alternator or transformer that supply them with power. This is illustrated in Fig. 2 for a single-phase motor, a three-phase motor, and a three-phase alternator.

It should be noted, therefore, that there is a fundamental difference

between a-c and d-c armature windings; *i.e.*, a-c windings are always open-circuited, whereas d-c windings are always closed-circuited.

The fact that a-c windings do not close is not always apparent, and this is particularly true in polyphase machines where the individual phases are interconnected. In the three-phase delta-connected winding, for example, each phase must be considered independently of the others when the open-circuit distinction is applied. In the three-phase star-connected winding, on the other hand, each phase must be regarded as the portion between any one of the line terminals and the *neutral point;* the electrical potential of the neutral or *star point* is always the same as a real or fictitious neutral at the alternator, the transformers, or the load. The armature

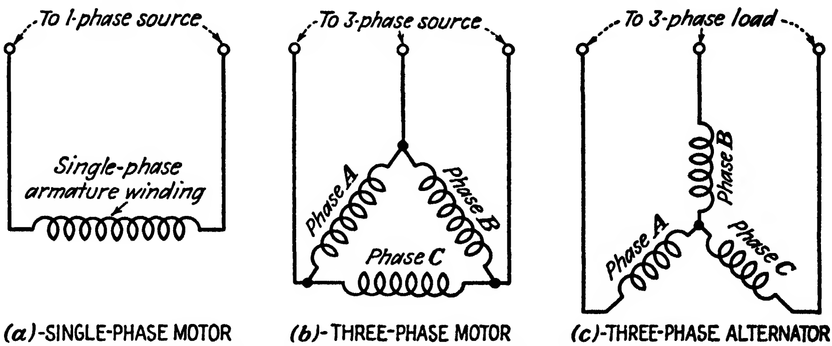


FIG. 2. Simplified sketches illustrating that a-c windings are *open-circuit* windings.

winding in the rotary converter may appear to be an exception to the open- and closed-circuit distinction, but this is not so if the d-c and a-c functions of the machine are considered separately. In the three-phase rotary converter, the armature winding should be regarded as a closed circuit when viewed from the d-c side; the same armature winding is delta-connected, with each phase open-circuited, when viewed from the a-c side. For the six-phase rotary converter, the armature winding, as before, is a closed circuit from the d-c end, and is mesh-connected, with each phase open-circuited, from the a-c end.

Types of D-c and A-c Windings

There are two general types of modern d-c armature winding, namely, *lap* and *wave*. The *frog-leg* winding is not a distinct type but a unique combination of a simplex-lap and a multiplex-wave winding. Both of these, lap and wave, are also used in a-c machines, but a third type, the *concentric* or *spiral* winding, is also employed. The latter, as will be discussed in detail subsequently, involves an arrangement in which the individual coils of a group, *i.e.*, a subdivided portion of the entire winding, are

arranged concentrically with respect to each other. When regarded from the point of view of current flow, the winding is seen to consist of a series of spirals.

In general, lap windings are used in polyphase motors, in some single-phase motors, and in most high-speed alternators. Wave windings are usually found on the rotors of certain polyphase motors. The concentric winding is employed mostly in small single-phase motors and in slow-speed alternators of rather large physical dimensions.

Parallel Paths in D-c and A-c Windings

There are always an *even* number of parallel paths in d-c armature windings. In simplex-wave windings the total armature current divides

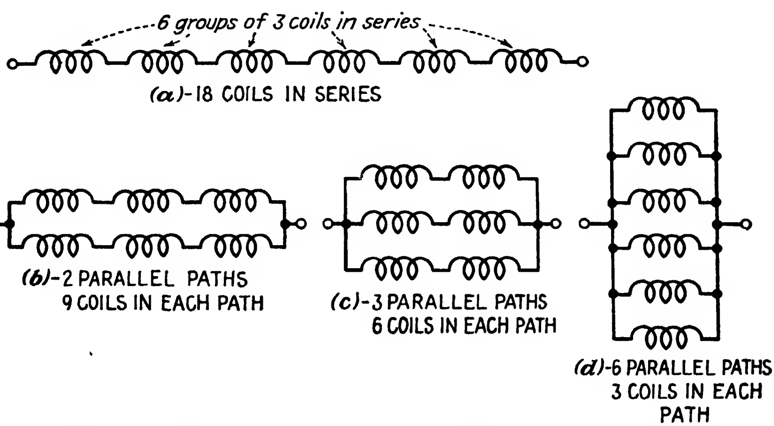


FIG. 3. Possible arrangements of 18 coils in one phase of a 6-pole armature winding.

into *two* parallel paths; in simplex-lap windings the total armature current divides into P parallel paths, where P, always an even number, is the number of poles in the machine. The number of parallel paths in duplex, triplex, quadruplex, etc., windings is, respectively, two, three, four, etc., times as many as in simplex windings. Thus, a *four*-pole simplex-wave winding has *two* parallel paths; a *six*-pole simplex-lap winding has *six* parallel paths; an *eight*-pole duplex-wave winding has *four* parallel paths; a *ten*-pole duplex-lap winding has *twenty* parallel paths.

Each phase of a-c armature windings can be one continuous series of coils from end to end or may be divided into any number of *identical* parallel paths. This is true regardless of the number of poles for which the armature is wound. Thus, each phase of a 4-pole winding having four identical coil groups in each phase can be a simple, continuous series circuit, in which case the total phase current passes through every coil; moreover,

it can be connected to have two or four parallel paths, under which condition each path carries one-half or one-fourth, respectively, of the total phase current. A 6-pole winding having six identical coil groups in each phase can have a simple series connection or two, three, or six parallel paths; a 12-pole winding having twelve identical coil groups in each phase can be series or can have two, three, four, six, or twelve parallel paths. Note that in each arrangement of parallel paths there is always exactly the same number of series coils in the individual parallel paths. Figure 3 illustrates the possible arrangements of 18 coils of one phase of a 6-pole a-c armature winding. Observe that there are, in this example, the series, the two-parallel, the three-parallel, and the six-parallel possibilities.

Arrangement of Coils in D-c and A-c Windings

All the coils of a d-c armature winding are identical and are placed in the slots of the core in regular succession; the coil ends of each coil are then connected to commutator bars similarly located with respect to the sides of the coils. The construction procedure is, therefore, entirely systematic, and the resultant winding is completely symmetrical in the sense that all coils and commutator connections follow each other systematically; *i.e.*, what is done for the first coil is repeated for every succeeding coil.

All the coils of lap windings or wave windings in a-c machines are identical; those used for concentric (spiral) windings have several shapes and sizes. However, when the coils of any of the windings indicated are placed in the slots of the core, it is done with complete regularity; *i.e.*, the procedure that is followed for one *set* or *group of coils* is repeated for every similar set or group of coils. But, and this is the important difference between d-c and a-c winding construction, when the individual coils are interconnected to form the completed a-c winding, it is necessary to join them together so that (1) the proper coils are grouped together to form *pole-phase* sections; (2) the proper pole-phase sections are combined to form the individual phases with the correct polarities; (3) the individual phases are interconnected to form the proper polyphase connection. Of course, in the single-phase winding, only pole and polarity groupings must be considered.

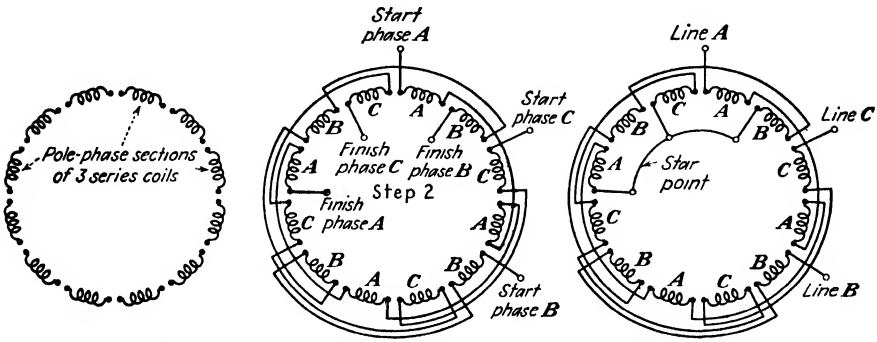
To illustrate the above discussion, consider a 36-coil armature winding arranged for 4-pole 3-phase star-connected operation.

STEP 1. Divide the 36 coils into 12 pole-phase sections, with three coils connected in series per section.

STEP 2. Labeling successive pole-phase sections *A*, *B*, *C*, *A*, *B*, *C*, etc., connect the *A* sections together to form one complete phase, making sure that this is done properly with regard to polarity; do the same for the *B* and *C* phases.

STEP 3. Interconnect the three phases A, B, and C to form a star connection.

Figure 4 indicates how this is done in the three steps outlined above.



(a)-STEP 1: 12 pole-phase sections with 3 series coils per section

(b)-STEP 2: Coils of individual phases shown connected together

(c)-STEP 3: Three phases shown interconnected to form a star connection

FIG. 4. Sketches illustrating method for arranging a 36-coil, 4-pole, 3-phase, star-connected winding.

Insulation for D-c and A-c Windings

Before the coils of a d-c or a-c winding are placed in an armature core, insulating lining material must be carefully provided in the slots. This is done to guard against possible grounding of the winding, even though the individual coils are themselves given a suitable covering of insulation. Moreover, if the winding is of the double-layer type, where each slot contains two coil-sides of two different coils placed one above the other, it is also necessary to provide an insulating strip between the two layers. The reason for this practice is that line voltage may exist between the two layers of coil-sides.

Where the individual coils are machine-formed, taped, dipped in an insulating varnish, and baked, no further insulations are necessary because the open core slots permit the insertion of the coil-sides in this carefully prepared manner. However, when slots are partially closed by overhanging teeth, a practice employed in the construction of many a-c machines, the coils cannot be completely formed in the manner indicated above. Instead, taping, dipping, and baking must be done after the individually formed coils are placed in the core by tediously slipping the wires into the slots one or more at a time. Since maximum voltage also exists between coil-sides, in the same layer, that are connected in different phases, it is necessary to provide added *phase insulation* between pole-phase sections. In Fig. 4*a* this would be in the spaces separating the 12 sections. This point will become clearer later when polyphase windings are discussed in detail and when photographs will illustrate the added insulation during the winding process.

Summary

1. The function of all armature windings, d-c and a-c, is to create magnetism.

2. All windings are arranged in definite symmetrical patterns in the slots of armature cores.

3. In a d-c machine the armature winding always rotates, but the magnetic field it creates is stationary in space.

4. In most a-c machines the armature winding (or windings) is stationary, but the magnetic field, which it creates, rotates. In those a-c machines where the armature winding rotates, the magnetic field may or may not remain stationary, but in any case it does not rotate at the same speed as does the winding.

5. In any d-c or a-c machine there is always relative motion between the armature winding (or windings) and its created magnetic field.

6. All d-c armature windings are closed-circuit windings; *i.e.*, they are reentrant windings.

7. All a-c armature windings are open-circuit windings.

8. There are two general types of d-c winding, namely, lap and wave.

9. There are three general types of a-c winding, namely, lap, wave, and concentric (spiral).

10. There are always an even number of parallel paths in d-c armature windings.

11. Since a-c armature windings are open-circuited, they may be single-circuit or many-circuit. If there is more than one circuit, the number of possible parallel paths must depend upon the number of identical sections that may be arranged. This will usually be determined by the number of poles for which the armature is wound.

12. All the coils of lap windings or wave windings, d-c or a-c, are identical.

13. Coils used for concentric (spiral) windings are of different shapes and sizes.

14. Regardless of the type of winding, the coils are always placed in the armature core with complete regularity. Once the system has been established, the procedure is one of repetition.

15. In a-c windings the individual coils are first joined together to form pole-phase sections, after which the proper pole-phase sections are combined to form the individual phases with the correct polarities. The individual phases are finally interconnected to form the proper polyphase connection, as, for example, star or delta.

16. The armature coils in all windings must be properly insulated so that electrical breakdown does not occur between coils inside and outside the slots, and between the coils and ground. The insulating preparation must be carefully done if these aims are to be achieved.

CHAPTER 2

Elementary Principles of A-c Machines

In the study of a-c armature windings it is important that the student have an elementary knowledge of a-c motor and generator (alternator) principles. It will, therefore, be the purpose of this chapter to review briefly some of the essential points that are thoroughly covered in texts dealing with electrical machines.* In this connection it will also be necessary to explain and define terms appearing repeatedly throughout the book.

Frequency of the Generated Alternating Voltage

In modern alternators, it is customary to place an armature winding on a ring type of stationary laminated steel core and mechanically rotate a set (an even number) of salient (shaped) poles inside the core. Relative motion, therefore, exists between the stationary conductors in the *stator* (stationary core) and the revolving poles. As a result, voltages are generated in the armature conductors.

Since the *direction* of the generated voltage in any armature-winding conductor depends upon whether the latter is cut by flux from a *north* or *south* pole, it should be clear that one complete positive and negative pulse of voltage, one *cycle*, will occur for every pair of poles. If the machine has only two poles (one pair), and if the speed of rotation is 1 revolution per second (60 revolutions per minute), the frequency will be $P/2$ cycles per revolution, where P is the number of poles on the rotating structure. It follows, therefore, that the frequency f in cycles per second of the generated voltage in an alternator depends upon both the number of *pairs of poles* and the number of *revolutions per second.* Thus,

$$f = \frac{P}{2} \times \frac{\text{rpm}}{60} = \frac{P \times \text{rpm}}{120} \tag{1}$$

where f = cycles per second
P = number of poles
rpm = revolutions per minute

* Siskind, C. S., "Electrical Machines—Direct and Alternating Current," McGraw-Hill Book Company, Inc.

Electrical Degrees

Alternators are usually designed to generate *sine waves* of alternating voltage. This is done by properly shaping the pole faces and arranging the armature winding in accordance with well-established practices. If the machine has two poles, one sine wave cycle is developed for each revolution, *i.e.*, for 360 mechanical degrees; and since *each cycle is said to occur in* 360 *electrical degrees*, it is seen that for two poles mechanical and electrical degrees are identical.

However, if there are four poles on the field structure, there will be two cycles for each complete revolution of 360 mechanical degrees. This implies that there will be 720 *electrical degrees* in the circumference of a four-pole machine. Moreover, for six-, eight-, ten-, etc., pole alternators there will be, respectively, 1,080, 1,440, 1,800, etc., electrical degrees for every 360 mechanical degrees. Or, to put it another way, every 360 electrical degrees is contained in $(2/P) \times 360$ mechanical degrees. Thus, in four-, six-, eight-, ten-, etc., pole alternators, each cycle of 360 electrical degrees occurs, respectively, in 180, 120, 90, 72, etc., mechanical degrees. In Fig. 4, for example, which schematically represents a four-pole machine, each pole-phase section covers 30 mechanical degrees, or 60 electrical degrees.

Speed of A-c Motors

Induction-type a-c motors employing armature windings, with which this book is mainly concerned, operate at speeds that depend upon two factors, namely, (1) the frequency of the source of supply and (2) the number of poles for which the machine is wound. Such machines tend to run at somewhat less than the so-called *synchronous speed*, which may be calculated by revising Eq. (1) so that it is written in terms of rpm. Thus,

$$\text{rpm (synchronous)} = \frac{120 \times f}{P} \tag{2}$$

The actual speed of induction motors is always less than the theoretically maximum synchronous speed, the difference being represented by what is termed the *slip*. If the latter is indicated as a decimal such as 0.04 or 0.06 and is represented by the symbol s, the actual speed becomes

$$\text{rpm (actual)} = \frac{120 \times f}{P} \times (1 - s) \tag{3}$$

EXAMPLE 1. Calculate the actual speed of a 4-pole 60-cycle induction motor having a slip of (*a*) 0.03; (*b*) 0.05.

Solution

(*a*) $$\text{rpm} = \frac{120 \times 60}{4} \times (1 - 0.03) = 1{,}746$$

(*b*) $$\text{rpm} = \frac{120 \times 60}{4} \times (1 - 0.05) = 1{,}710$$

EXAMPLE 2. (*a*) At what speed will a 6-pole 60-cycle induction motor run if the slip is 0.045? (*b*) What will be the speed of the same motor if connected to a 25-cycle source, assuming the same slip as in (*a*)?

Solution

(*a*) $$\text{rpm} = \frac{120 \times 60}{6} \times (1 - 0.045) = 1{,}146$$

(*b*) $$\text{rpm} = \frac{120 \times 25}{6} \times (1 - 0.045) = 477.5$$

Note particularly that *the speed* of this type of motor *is directly proportional to the frequency* [compare parts (*a*) and (*b*) of Example 2] *and is inversely proportional to the number of poles* [compare parts (*a*) of Examples 1 and 2]. It is especially important to remember this, because induction motors lend themselves to major speed changes by rewinding or reconnecting an armature winding for different numbers of poles or by altering the supply frequency in some way. This problem will be considered in detail in subsequent chapters.

Generated Voltage in Alternators

As in d-c generators, the generated voltage in alternators depends directly upon (1) the speed at which they are operated, (2) the flux created by the poles, and (3) the number of series turns (or conductors) in the winding. Without attempting to derive the general expression for the magnitude of this voltage per phase when the emf varies sinusoidally (like a sine wave), the voltage equation may be written as follows:

$$E = 4.44\, f\phi N \times 10^{-8} \tag{4}$$

where E = effective generated volts per phase
f = frequency, in cycles per second
ϕ = flux created by each pole, in maxwells
N = number of series turns per phase

It should be noted that the frequency term f takes into account the number of poles and the speed [see Eq. (2)]; also, term N is assumed to indicate that the generated voltages in all the conductors making up the total number of turns add arithmetically. (The latter is not strictly true, as will be pointed out later.)

EXAMPLE 3. Calculate the generated voltage in each phase of an alternator, given the following particulars: $P = 6$; rpm $= 1{,}200$; $\phi = 3.2 \times 10^6$; $N = 156$

Solution

$$f = \frac{P \times \text{rpm}}{120} = \frac{6 \times 1{,}200}{120} = 60$$

$$E = 4.44\, f\phi N \times 10^{-8} = 4.44 \times 60 \times 3.2 \times 10^{6} \times 156 \times 10^{-8} = 1{,}330 \text{ volts}$$

The Pitch Factor

In a-c armature windings of the lap or wave type, the individual coils are formed so that the two sides normally occupy slots that are equal to or less than a *pole pitch*. (A *pole pitch* is the circumferential distance between the centers of two adjacent poles.) This is similar to the practice employed in the construction of d-c armature windings. Remembering that 1 cycle covers a distance of 360 electrical degrees and that this distance is spanned by *two* adjacent poles, it follows that a coil span is 180 electrical degrees or less.

If the distance between the coil-sides of individual coils of a winding is exactly 180 electrical degrees, they are called *full-pitch* coils; the winding is then known as a *full-pitch winding*. However, if the coil span of such coils is less than 180 electrical degrees, they are called *fractional-pitch* coils; the winding is then known as a *fractional-pitch winding*.

It was previously pointed out that the term N in Eq. (4) is assumed to indicate, for one thing, that the generated voltages in the individual conductors of the separate coils add arithmetically. This is partly true if the winding is full-pitch, for only then will the generated voltages in the two sides of individual coils, although varying from instant to instant, be exactly equal; under this condition the voltages generated in the two sides of each coil are said to be *in phase* with each other. On the other hand, when fractional-pitch windings are used, and this is most generally the case, the generated voltages in the two coil-sides of individual coils are no longer in phase; this means that the actual emf at the terminals of each coil will be *less* than that existing in full-pitch coils, other conditions remaining the same. Therefore, Eq. (4) must be modified by introducing a *reducing factor* to take account of fractional-pitch windings; this is called the *pitch factor* and is represented by the symbol k_p.

If the circumferential distance between the coil-sides of individual coils is expressed by $A°$, in electrical degrees, then

$$k_p = \sin \frac{A°}{2} \tag{5}$$

Figure 5 illustrates several possible coils for a machine having nine slots per pole (36 total slots and 4 poles, for example), in which the coil pitches are 180, 160, 140, and 120 electrical degrees. Pitch factors k_p are shown calculated and are, respectively, 1.0, 0.985, 0.940, and 0.866.

EXAMPLE 4. Calculate the generated voltage per phase in Example 3 if the pitch factor is 0.940.

Solution

$$E = 1{,}330 \times 0.940 = 1{,}250 \text{ volts}$$

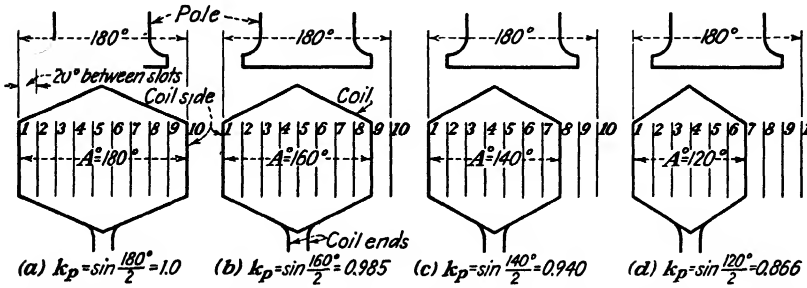


FIG. 5. Sketches illustrating method for calculating the *pitch factors* k_p of a machine having nine slots per pole.

The Distribution Factor

In addition to the pitch factor, it is generally necessary to apply another reducing factor to Eq. (4) to take account of the fact that the generated voltages in the coils connected in series in any pole-phase group (see Fig. 4) are not in phase with each other. This implies that the voltage developed in any pole-phase group is *less* than would exist in a *single* coil having exactly the same number of turns of wire as in the entire group. Windings in which several coils are used in each pole-phase group are called *distributed windings* and have superior advantages over those in which single coils are used for each pole per phase. The latter are called *concentrated windings* and are seldom found in modern machines.

The factor that must be used for distributed windings to further reduce the generated voltage, given by Eq. (4), is called the *distribution factor* and is symbolized by k_d. It may be calculated by using the expression

$$k_d = \frac{\sin \dfrac{nB^\circ}{2}}{n \sin \dfrac{B^\circ}{2}} \tag{6}$$

where n = number of coils in each phase group
B° = electrical degrees between adjacent slots

EXAMPLE 5. In a 36-slot 4-pole 3-phase machine there are three coils in each phase group ($36/4 \times 3$). The number of electrical degrees per

slot, $B°$, is 20° (180/9). Calculate the distribution factor and the new generated voltage for Example 4.

Solution

$$k_d = \frac{\sin \frac{3 \times 20°}{2}}{3 \times \sin \frac{20°}{2}} = \frac{\sin 30°}{3 \times \sin 10°} = \frac{0.5}{3 \times 0.1{,}736} = 0.960$$

$$E = 1{,}250 \times 0.960 = 1{,}200 \text{ volts}$$

Figure 6 illustrates a group of three coils connected in series, in which each coil has a span of 140 electrical degrees ($k_p = 0.940$) and for which the distribution factor k_d is 0.960.

EXAMPLE 6. Calculate the distribution factor k_d for a winding in which there are six coils in each phase group and where there are 10 electrical degrees between slots.

Solution

$$k_d = \frac{\sin \frac{6 \times 10°}{2}}{6 \times \sin \frac{10°}{2}} = \frac{\sin 30°}{6 \times \sin 5°}$$

$$= \frac{0.5}{6 \times 0.0872} = 0.956$$

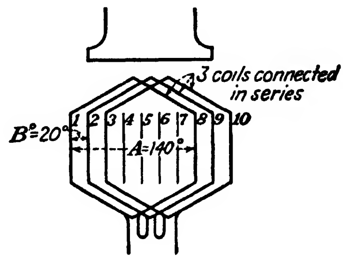


FIG. 6. Sketch illustrating three coils in a distributed winding for which $k_p = 0.940$ and $k_d = 0.960$.

The General Voltage Equation for Alternators

Having considered the pitch and distribution factors, it should now be apparent that Eq. (4) may be applied only to concentrated, full-pitch windings, under which condition k_p and k_d are both unity.

However, when the winding is distributed and fractional pitch, as is generally the case, the reducing factors k_p and k_d must be determined and applied in the calculation. This was done in Examples 4 and 5.

To simplify the procedure in determining the effective generated voltage per phase for any winding, it is customary to combine all terms in a single general equation, written as follows:

$$E = 4.44\, f\phi N k_p k_d \times 10^{-8} \tag{7}$$

Note particularly that k_p and k_d are always less than unity for fractional-pitch and distributed windings. This merely means that the voltages generated in the individual conductors and turns of a winding do not add arithmetically; they do in fact add vectorially, a mathematical operation that is performed by the use of the pitch and distribution factors.

Example 7. Each phase of a 3-phase 4-pole 1,800-rpm alternator has 128 turns. If the stator core has 48 slots, and the coil pitch is from slot 1 to slot 10, calculate the generated voltage per phase, assuming that each pole produces 7.62×10^5 maxwells.

Solution

$$f = \frac{4 \times 1{,}800}{120} = 60 \text{ cycles per second}$$

$$A° = \frac{9}{12} \times 180° = 135° \qquad k_p = \sin \frac{135°}{2} = 0.924$$

$$B° = \frac{180°}{12} = 15° \qquad k_d = \frac{\sin \dfrac{4 \times 15°}{2}}{4 \sin \dfrac{15°}{2}} = \frac{0.5}{4 \times 0.1305} = 0.958$$

$$E = 4.44 \times 60 \times 7.62 \times 10^5 \times 128 \times 0.924 \times 0.958 \times 10^{-8} = 230 \text{ volts}$$

Two-phase Windings

A *two-phase system* is a combination of circuits energized by alternating electromotive forces which differ in phase by 90 electrical degrees. (In

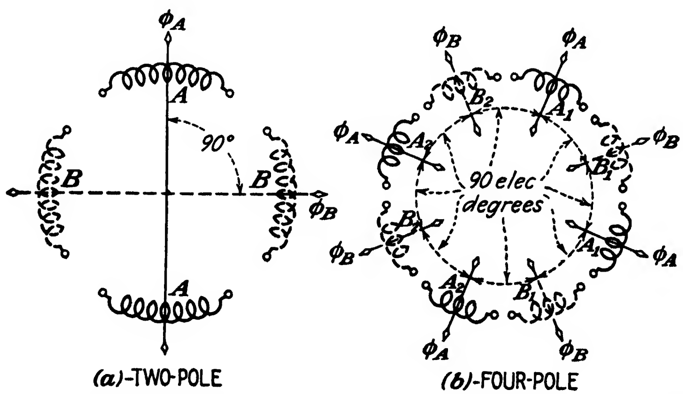


Fig. 7. Schematic sketches illustrating arrangement of windings for a two-phase system

practice the phases may vary several degrees from the specified angle.) Such a system may be provided by an alternator having two identical armature windings that are displaced from each other in space (on the armature core) by 90 electrical degrees. A three-phase system (see next article) may also be converted into a two-phase system by employing a suitable combination and connection of transformers.

In the two-phase two-pole alternator, one set of two coils, connected to produce a north and south pole, creates a magnetic field along an axis that is exactly 90 electrical (or mechanical) degrees from the axis of another

magnetic field; the latter is created by a second set of two coils placed at right angles to the first set. Figure 7*a* illustrates the schematic arrangement of the two sets of coils *A* and *B* for the two-pole two-phase system. Where there are four or more poles there must be four or more sets of coils creating as many magnetic fields. Figure 7*b* illustrates the schematic arrangement of four sets of coils *A* and *B* in which the angular displacement between adjacent coils is 90 electrical, or 45 mechanical, degrees. No attempt is made here to indicate the actual arrangement of the coils in the slots or the manner in which connections are made.

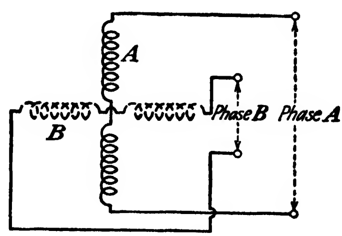


FIG. 8. Simplified sketch illustrating a four-wire two-phase system.

Figure 8 illustrates a simplified method of representing a two-phase system. Note that the windings are placed at right angles (90°) to each other and are entirely independent of each other. This arrangement is designated a *four-wire two-phase* system.

The two windings of a two-phase system may be interconnected to form a *three-wire two-phase* system or a *five-wire quarter-phase* (*four-phase*) system.

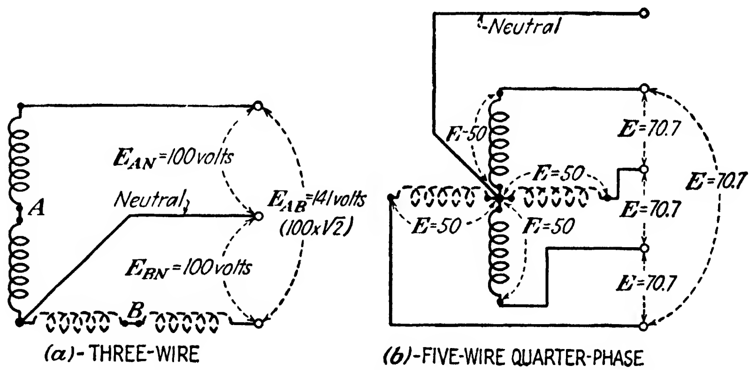


FIG. 9. Two-phase systems in which the two windings are interconnected.

These are shown in Fig. 9. If it is assumed that the voltage across each of the two entire windings *A* and *B* is 100 volts, then the voltage between the outer wires of the three-wire system, Fig. 9*a*, will be $100 \times \sqrt{2}$ or 141 volts. In the five-wire system (Fig. 9*b*) the voltage between adjacent line wires will be $50 \times \sqrt{2}$ or 70.7 volts.

Three-phase Windings

A *three-phase system* is a combination of circuits energized by a-c electromotive forces which differ in phase by 120 electrical degrees. (In practice

the phases may vary several degrees from the specified angle.) Such a system may be provided by an alternator having three identical armature windings that are displaced from each other in space (on the armature core) by 120 electrical degrees. A two-phase system may also be converted into a three-phase system by employing a suitable combination and connection of transformers.

In the three-phase two-pole alternator, one set of two coils, connected to produce a *north* and *south* pole, creates a magnetic field along an axis

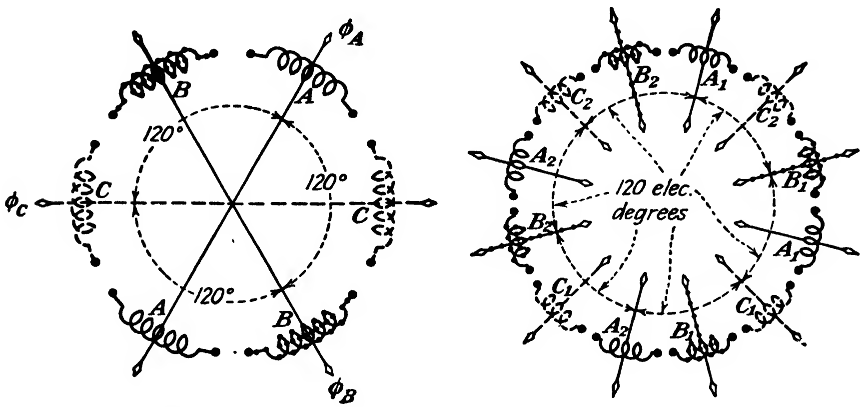


FIG. 10. Schematic sketches illustrating arrangement of windings for a three-phase system.

that is exactly 120 electrical (or mechanical) degrees from each of the axes of two other magnetic fields; the latter are created by two other sets of coils placed 120 electrical degrees from the first set and also 120 electrical degrees with respect to each other. Figure 10*a* illustrates the schematic arrangement of the three sets of coils *A*, *B*, and *C* for the two-pole three-phase system. Where there are four or more poles there must be four or more sets of coils creating six or more magnetic fields. (Each two sets of coils creates one magnetic field.) Figure 10*b* illustrates the schematic arrangement of six sets of coils *A*, *B*, and *C*, in which the angular displacement between coils of the proper polarity (to be explained later) is 120 electrical degrees. No attempt is made here to indicate the actual arrangement of the coils in the slots or the manner in which connections are made.

There are two common methods of interconnecting the three windings to form a three-phase system. These are, namely, (1) the *star* connection and (2) the *delta* connection, so designated because the simplified schematic sketches usually drawn to represent these connections resemble the three-

pointed star and the Greek letter delta (Δ). They are shown in Fig. 11. Note particularly that in the drawings of the star and delta sketches, phases A, B, and C are shown having the same general directions as those indicated by Fig. 11a. Now then, if it is assumed that the voltage across each of the three phases is 100 volts, the voltage between any two line wires in the star connection will be $100 \times \sqrt{3}$ or 173.2 volts, and the voltage between any two line wires in the delta connection will remain 100 volts.

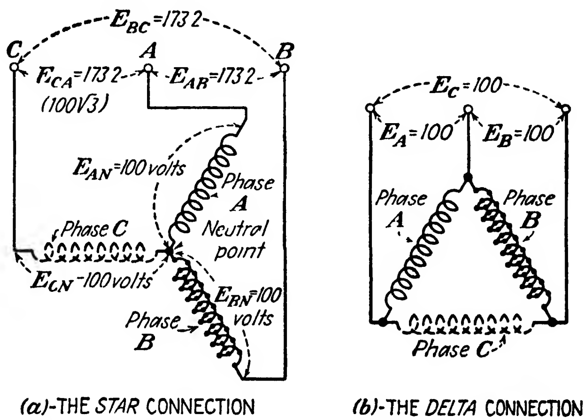


FIG. 11. Three-phase systems in which the three windings are interconnected.

Summary

1. In modern alternators, an armature winding is placed on a stationary ring type of laminated steel core, and a set of *north* and *south* poles is rotated inside the core.

2. One cycle of alternating voltage will be generated for every pair of poles.

3. The frequency in cycles per second is directly proportional to the number of pairs of poles and to the speed in rpm.

4. The circumferential distance between the centers of adjacent poles is 180 electrical degrees.

5. One cycle is generated in 360 electrical degrees.

6. Every 360 electrical degrees is contained in $(2/P) \times 360$ mechanical degrees.

7. The synchronous speed of an induction type of motor is directly proportional to the supply frequency and inversely proportional to the number of poles.

8. The actual speed of an induction motor is always less than the synchronous speed, the difference being termed the slip.

9. The generated emf in one phase of an alternator is directly proportional to the frequency, flux, and the number of series turns.

10. A full-pitch winding is one in which the span of the individual coils is 180 electrical degrees.

11. A fractional-pitch winding is one in which the span of the individual coils is less than 180 electrical degrees.

12. The pitch factor is the number, always less than unity for a fractional-pitch winding, which takes into account the out-of-phase relationship in the generated voltages of two sides of a fractional-pitch coil.

13. A concentrated winding is one in which there is only one coil for each phase per pole.

14. A distributed winding is one in which there are several coils in series for each pole-phase group.

15. The distribution factor is a number, always less than unity for a distributed winding, which takes into account the out-of-phase relationship in the generated voltages of the individual coils in a pole-phase group.

16. The generated voltage per phase is directly proportional to the pitch and distribution factors. The pitch factor becomes less with decreasing coil spans; the distribution factor becomes less with an increase in the number of coils per phase group.

17. A two-phase system is a combination of circuits energized by alternating electromotive forces which differ in phase by 90 electrical degrees.

18. There are three general types of the two-phase system, namely, (*a*) the four-wire system, (*b*) the three-wire system, and (*c*) the five-wire quarter-phase system.

19. A three-phase system is a combination of circuits energized by a-c electromotive forces which differ in phase by 120 electrical degrees.

20. There are two general types of the three-phase system, namely, (*a*) the star connection and (*b*) the delta connection.

21. In a three-wire two-phase system, the voltage between the outer wires is equal to $\sqrt{2}$ times the voltage per phase.

22. In a five-wire quarter-phase system, the voltage between adjacent line wires is equal to $\sqrt{2}$ times the voltage per phase to neutral. (The voltage per phase to neutral is one-half of the entire phase voltage.)

23. In a star-connected three-phase system, the voltage between any two line wires is equal to $\sqrt{3}$ times the voltage per phase, *i.e.*, the voltage between line and neutral.

24. In a delta-connected three-phase system, the line voltages are the same as the phase voltages.

CHAPTER 3

The Single-phase Concentric (Spiral) Winding

Several general methods are used in winding slotted type cores for small single-phase motors. One of the most common of these is to arrange each group of coils under a pole (a pole group) into a sort of concentric configuration. When the current path is traced through one such properly connected set of coils, the conductors seem to form a *spiral* around a portion of the core. It is for this reason that windings constructed in this manner and considered in this chapter are called *concentric windings* or *spiral windings.*

Principle of the Spiral Winding

It was previously pointed out that the function of the current-carrying armature winding is to create flux. For each group of coils, this flux results only because definite magnetic *north* and *south* poles are formed. True, the poles are formed over a discontinuous body of steel represented by teeth and slots, and the polarities of these poles are changing from instant to instant; but the poles are just as effective as those produced by steady currents in d-c machines.

Consider Fig. 12, which represents a portion of a slotted stator core of a small a-c motor. Assume that there is a large conductor in each of the slots carrying current in the direction indicated. Using the right-hand rule to determine magnetic polarity, conductors *a* and *b* may be considered as one turn of wire acting on tooth 3 to produce a *north* pole; likewise, conductors *c* and *d* may be considered as one turn of wire acting on tooth 3 and teeth 2 and 4 to produce *north* poles; also, conductors *e* and *f* may be considered as one turn of wire acting on teeth 3, 2, and 4 and on teeth 1 and 5 to produce *north* poles. Note particularly that tooth 3 is acted upon by all six conductors so that it will have the greatest magnetic strength; teeth 2 and 4 are acted upon by *four* conductors so that their magnetic strengths will be less; teeth 1 and 5 are acted upon by only *two* conductors so that their magnetic strengths are the least. To indicate the relative strengths, the teeth have been labeled with *N* letters of different sizes.

Obviously, an actual winding does not consist of single elementary con-

ductors each carrying independent currents, as shown in Fig. 12. A much more practical way of accomplishing the same result is, of course, to use a single continuous wire wrapped around the teeth, as represented by Fig. 13. And, if the current directions are the same as those previously shown, the

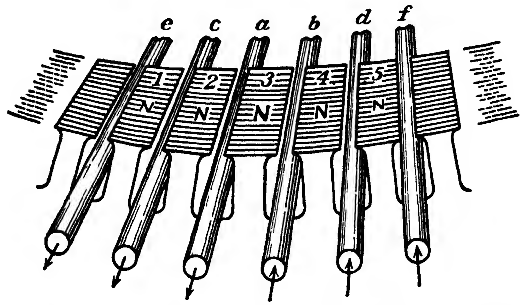


FIG. 12. Sketch illustrating portion of a stator core that is magnetized by current-carrying conductors.

polarities will be similar. A careful study of the diagram should make it clear that the three-turn coil forms a sort of *spiral* around the five teeth, and it is this similarity that is responsible for the name *spiral winding*.

To create strong magnetic poles it is necessary to have many *ampere-*

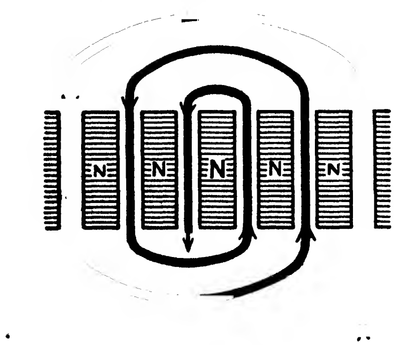


FIG. 13. Modification of Fig. 12 showing the derivation of the term *spiral winding*.

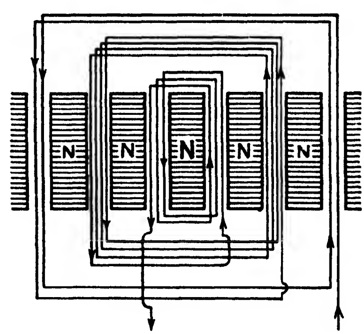


FIG. 14. Further modification of Fig. 12 showing a spiral winding in which each coil has several turns.

turns (*i.e.*, the product of amperes and turns). This may be accomplished by using a few turns of wire and much current or, vice versa, by having many turns of wire and a moderately low current. Since the latter is more practical in small machines, an arrangement similar to that shown in Fig. 14 is generally employed. In this diagram, three coils of wire are wound *concentrically* around the five teeth to form the proper teeth polarities. In practice it is customary to have a different number of turns in

each of the coils, the purpose being to create a flux-density distribution in the air gap, between stator and rotor, that is sinusoidal, *i.e.*, varying like a sine wave.

If the coils are preformed on special equipment, previous to being placed in the proper slots, they constitute a group of concentrically shaped coils as illustrated by Fig. 15. Each of the coils has the requisite number of turns. Sometimes the individual coils of a pole group are formed separately, inserted in the slots, and then interconnected in series. More often, where high production schedules must be maintained, the complete pole group is wound on a *gang mold* with a continuous wire from end to end; this practice eliminates the soldering and taping operation that is necessary when the wire is cut for the individual coils of the group. The diagram illustrates clearly why the terms *spiral* and *concentric* are both applied to the same type of winding.

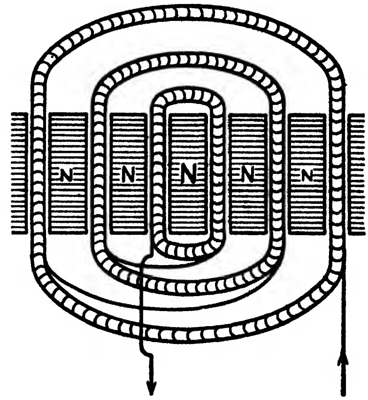


Fig. 15. Sketch illustrating one pole group of three concentrically formed coils.

Mush, or Hit-or-miss, Coils

In winding coils for small machines where many turns of comparatively small wire are used, it is generally difficult and time-consuming to arrange the wires in systematic layers. A more satisfactory practice is to permit the wires to settle haphazardly, *i.e.*, "hit or miss," in the winding space. Obviously, this method of winding coils requires more slot room than a procedure in which wires are carefully laid side by side and one above the other. The term *mush* or *hit-or-miss* is often applied to coils wound in this manner. They are used almost exclusively for concentric or spiral windings and are particularly adaptable to the construction of coils made in gang molds. The coil winder is, however, quite careful not to cross the wire from one side of a mold to the other; doing so tends to subject the insulation on the wires to mechanical and electrical failure, although the use of high-grade insulating materials on the wire lessens such tendency. Another reason for the use of mush coils is that good design ordinarily requires partially closed slots, *i.e.*, slots that have overhanging teeth. Under this condition it is impossible to use formed coils that would require open slots; the individual wires of the gang-mold untaped coils must be slipped through the narrow openings between the teeth one or two at a time so that they drop into the slots hit or miss.

Single-layer Winding

Unlike most lap and wave types of winding found on both d-c and a-c armatures, where each slot contains two coil-sides one on top of the other, the a-c spiral winding is single-layer because there is only one coil-side in each slot. Moreover, the separate coils that make up a coil group are of different sizes; this should be clear from an inspection of Fig. 15. In its construction, therefore, it is necessary to insert the smaller coil in the two inner slots, surround this with a second coil whose axial and circumferential lengths are larger, then follow this up with as many additional larger coils as are required. And, except for a second similar spiral winding which must be placed over the first one in machines of the so-called *split-phase* type, the insertion of the coils and their interconnection completes the job.

Connecting a Complete Concentric Winding

It was previously pointed out [Chap. 2, Eq. (2)] that the speed of an induction type of motor depends upon the number of poles for which the armature is wound; *the speed is,* in fact, *inversely proportional to the number of poles.* When connected to a 60-cycle source, for example, a 2-pole machine will operate at something less than 3,600 rpm, a 4-pole machine at slightly less than 1,800 rpm, a 6-pole machine at a little less than 1,200 rpm, etc.

Moreover, the number of poles for which the motor is wound is determined by the number of pole groups of coils, each pole group being similar to that illustrated by Fig. 15. Therefore, before a machine is wound, it is necessary to divide the core arbitrarily into as many equal parts as the number of desired pole groups. The winder then proceeds to place a group of concentrically formed coils into each division of slots and teeth in accordance with the arrangement previously discussed. As the final step, it remains only to interconnect the winding so that the magnetic polarities created by successive pole groups are, at any instant, opposite, *i.e., north, south, north,* etc.

To illustrate, assume a 24-slot stator core to be wound for four poles. Dividing the core into four equal parts gives six slots per pole. A three-coil group will, therefore, be placed into each division, after which the pole groups are joined together to yield, at any instant, poles of opposite polarity. Figure 16 represents a sketch of such a winding. It should be particularly noted how the four pole groups are interconnected so that four successive *north, south, north, south* poles are created. (Obviously, the indicated polarities change every half cycle.)

Whenever it becomes desirable to spread each pole group over a slightly wider area, so that the center of the pole occupies a space that is more than one-tooth width, a second scheme of concentric coils may be employed.

This is shown in Fig. 17 for the same combination of slots and poles as in Fig. 16. In this arrangement *the adjacent outer coil-sides of successive coil groups fall into the same slot.* A special point should, however, be made of the fact that all the wires in any one slot must always carry currents in the same direction at any given instant, regardless of the coil arrangement.

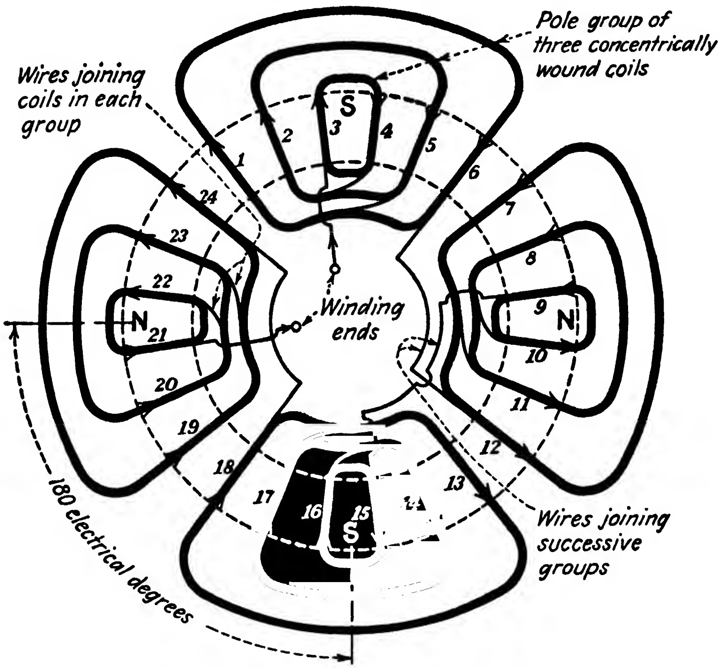


Fig. 16. Concentric winding for a four-pole stator core containing 24 slots.

The Skein Winding

An extremely common modification of the concentric type of winding, and one that accomplishes essentially the same result as the latter without the need of making several coils of different sizes, is the so-called *skein winding.* As the name implies, it is one in which each pole group is wound from a single skein of wires. In practice the skein of wires having the proper number of turns and length is looped back and forth through the slots of the core to form a pole; this process is then repeated to form as many additional poles as are required.

To understand how a skein winding is constructed and why it is merely a modification of the type previously discussed, *i.e.*, the concentric winding, it will be desirable to study the elemental steps in its evolution. Consider Fig. 18*a*, which represents six conductors placed in six slots of a stator core,

carrying currents in the directions indicated to create a *south* pole. Since it is absolutely immaterial how these conductors are connected together to create this *south* pole, so long as the current *directions* are not disturbed, a second possibility, other than the spiral connection shown in Fig. 13, is illustrated by Fig. 18*b*. Note that the current passes through the conductors in the following order: *a* to *e*, *e* to *c*, *c* to *d*, *d* to *b*, and finally from

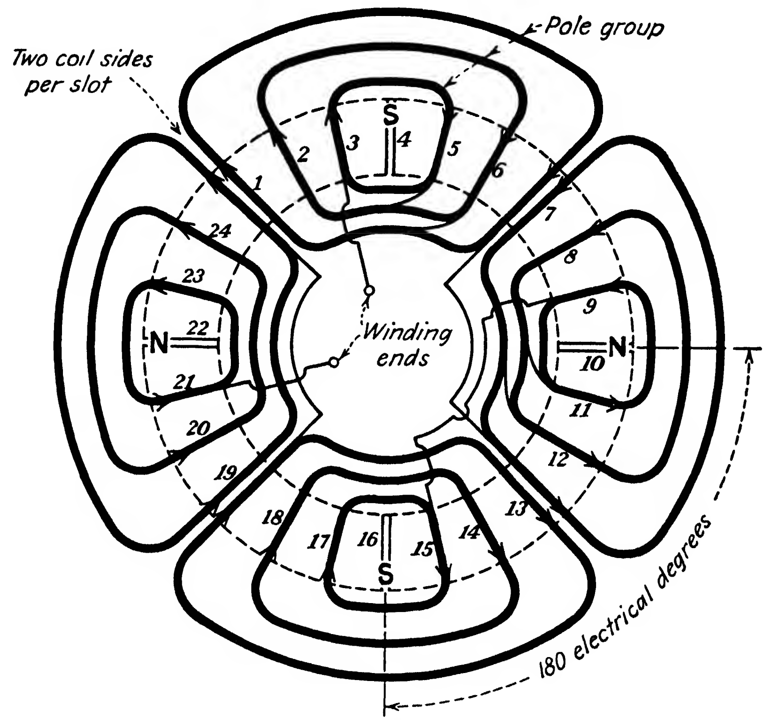
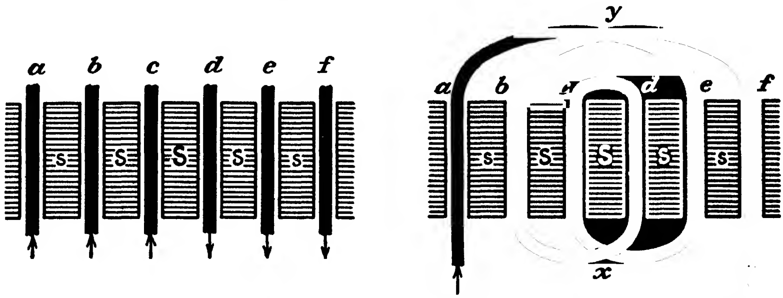


FIG. 17. Concentric winding for a four-pole stator core containing 24 slots. Note that slots 1, 7, 13, and 19 have coil-sides from the outer coils of adjacent pole groups.

b to *f*. Observe also that this pole could have been formed by using a single conductor of the proper length in the following manner: (1) Bend the wire in half; (2) place conductors *c* and *d* into the two inner slots and pull the extended wires until the looped part on the opposite side touches the core; (3) a half twist is made so that the wires cross, as at *x*; (4) loop the wires back through the next outside slots for conductors *b* and *e*, pulling the extended wires tightly until the looped parts on the opposite side touch the core; (5) another half twist is made so that the wires cross again, as at *y*; (6) loop the wires back through the outside slots for conductors *a* and *f*. Now then, if the current passes up in slot *a* and down in slot *f*, the

directions will be correct to create a *south* pole, since such directions will be exactly similar to those of Fig. 18*a*.

The actual winding, of course, has many conductors in each slot and not a single wire, as shown in Fig. 18. Assuming for simplicity that a correctly



(*a*)-SIX CURRENT-CARRYING CONDUCTORS SHOWN MAGNETIZING STATOR CORE

(*b*)-WIRE SHOWN LOOPED BACK AND FORTH THROUGH SLOTS TO MAGNETIZE STATOR CORE AS IN (*a*)

FIG. 18. Sketches illustrating first steps in evolution of *skein winding*.

measured skein of three turns was prepared, it would be looped back and forth in exactly the same way as previously outlined; the pole group would then appear like Fig. 19. Tracing the current flow through the wires would then result in the following sequence: *a* to *e* to *c* to *d* to *b* to *f* and back to *a*; the same sequence is repeated twice to complete the tracing of the three-turn skein.

To further illustrate how the actual skein and the completed pole group appear, Fig. 20 is given. In examining these sketches it should be understood that the actual skein length, Fig. 20*a*, must be very carefully measured to the end so that the final loop fits snugly, without slack, against the next inner bundle of wires. For most practical purposes this length can be readily determined by forming a single wire into the slots in exactly the same way as the skein of wires is actually arranged; obviously, careful allowance must be made for the bundle of wires that is represented by the single wire. In most cases it will be necessary to make several trial skeins and winding tests before a suitable size is found.

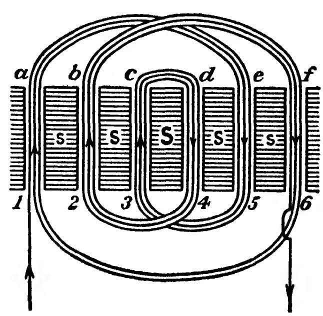
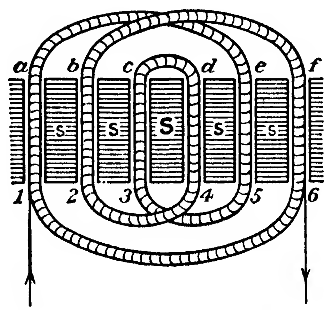


FIG. 19. Sketch illustrating a three-turn *skein* winding of one pole group.

It should not be inferred from what has been said thus far about skein windings that there is only one bundle of wires in each slot. Although this may be true in some special cases, it is usually more practical to pass

the skein back and forth through some of the slots twice or even three times. The reason for this practice is twofold, namely: (1) Skeins of fewer turns are easier to handle, and (2) it is generally more satisfactory, from the standpoint of machine operation, to have different numbers of wires in the various slots. Thus, for example, in Fig. 20, the skein might be passed once through slots *c* and *d*, twice through slots *b* and *e*, and once through slots *a* and *f*.

(a)-SKEIN OF MANY TURNS OF WIRE FOR ONE POLE GROUP



(b)-SKEIN SHOWN PLACED IN SIX SLOTS OF A STATOR CORE

FIG. 20. Sketches illustrating construction of skein and its arrangement in the stator core.

After all the pole groups have been properly formed by the skeins, they are interconnected in exactly the same manner as illustrated by Figs. 16 and 17, to create a succession of *north-south* poles.

Summary

1. A concentric, or spiral, winding is one in which each pole group is formed so that the current may be traced through wires in the slots to give the effect of a spiral around a portion of the core.

2. When each pole group consists of a set of coils of different size, each larger coil fitting around an inner smaller coil, the effect is like joining together a set of concentrically shaped coils; the name *concentric winding* is, therefore, appropriate.

3. The conductors surrounding a small part of a stator core in each pole group of a spiral winding creates the strongest magnetic field at the center; the field diminishes in strength toward the outside of the spiral.

4. The fundamental reason for statement 3 is that any turn of wire creates flux only *within*, never outside, the turn. Thus, in any spiral wind-

ing there are more ampere-turns acting on the center section than on any other part of the pole section.

5. In some concentric winding constructions, the individual coils of each pole group are formed separately, after which they are interconnected in series.

6. In other concentric winding constructions, a complete pole group is wound on a gang mold with a single continuous wire from end to end.

7. A mush, or hit-or-miss, coil is one in which the individual wires of a coil settle into the winding space haphazardly, as distinguished from a systematic arrangement of wires in layers and rows.

8. Mush coils are most common on small machines, since they are simpler and quicker to wind.

9. Mush coils must be used in machines in which the stator core has partially closed slots; the individual wires must be slipped through the narrow openings between the teeth, one or two at a time.

10. Concentric windings are generally single-layer in the sense that there is but one coil-side per slot. They differ from the lap and wave types, found in both d-c and a-c armatures, where there are two coil-sides per slot; the latter are double-layer windings.

11. There are always as many pole groups as poles in concentric windings. In general, the number of pole groups determines the speed of induction-type machines.

12. Successive pole groups in conventional concentric windings produce opposite polarities.

13. In general, the number of slots in a stator core is divisible by the number of poles for which the machine is wound.

14. In some arrangements of concentric-type windings, it is desirable to place the outer coil-sides of successive coil groups into the same slot. This makes it possible to spread each coil group over a slightly wider area.

15. A skein winding is a modification of the concentric winding.

16. A skein winding is one in which each pole group is wound from a single skein of wires. This practice eliminates the necessity of forming a set of coils that are different in size for each pole.

17. The skein always contains several turns of wire and must be properly measured so that the final loop fits snugly, without slack, against the next inner bundle of wires.

18. A skein may be measured for length by forming a single wire into the slots in exactly the same way as the skein of wires is actually arranged.

19. It is frequently desirable, in the construction of the skein winding, to pass the skein back and forth through some of the slots twice or even three times. This practice makes it easier to insert the winding, since there are fewer wires in the bundle; it also permits the winding to have different numbers of wires in the various slots.

CHAPTER 4

Windings for Repulsion-type Motors

The general principles of spiral and skein windings discussed in Chap 3 are applicable to several types of the single-phase motor There are, however, a number of constructional variations of the simple arrangements indicated by Figs 16, 17, and 20, these depend upon (1) the number of slots and teeth in the core, (2) whether the motor is a repulsion or split-phase type, (3) whether the coil groups are to be connected in the conventional manner or for consequent-pole operation, and (4) whether the motor is to be connected for a single-voltage operation or for either 115- *or* 230-volt operation This chapter will deal with some of the practical winding arrangements generally used on such modern machines

Stators for Repulsion-type Motors

There are three general classifications of the repulsion type of motor,* namely, (1) the repulsion-start, (2) the repulsion, and (3) the repulsion-induction They differ in their operating performances only because their rotor constructions and brush mechanisms are different, all have similar stator cores and windings

Repulsion-type motors in the smaller sizes (1/8 to 3/4 hp) generally have stators in which there are 24, 32, 36, or 48 slots In some of the larger machines (ratings up to 15 hp) it is customary to use stator cores having more than 48 slots However, in most cases *the number of slots divided by the number of poles is an integer* Thus 24-, 32-, 36-, and 48-slot stators are generally used for two- and four-pole motors, six-pole machines usually employ 36-, 48-, 54- and 60-slot stators, and 32-, 48-, 56-, and 64-slot stators may be wound for eight-pole operation Motors wound for more than eight poles are extremely rare because, for single-phase service, they are expensive to build and quite inefficient The 36-slot stator is undoubtedly used in greater numbers than any of the others This is true because (1) it can be wound for two-, four-, and six-pole operation, so that a single lamination can serve for the three most popular speeds, *i e* , 3,600,

* SISKIND, C S , "Electrical Machines," Chap 10, McGraw-Hill Book Company, Inc

1,800, and 1,200 rpm*; (2) it is the most desirable lamination, from the standpoint of satisfactory motor performance, for 1/6-, 1/4-, and 1/3-hp motors, the sizes that are manufactured in the greatest numbers. Figure 21 is a photograph of a typical 36-slot stator ready for winding.

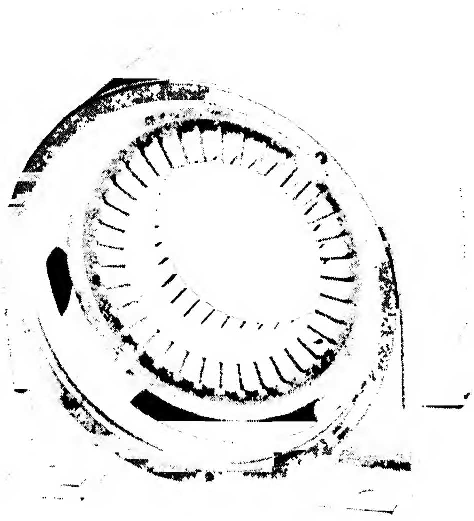


FIG. 21. Unwound 36-slot stator used for small single-phase motors. (*Reliance Electric and Engineering Co.*)

Windings for Repulsion Motors

Only *one* complete concentric or skein winding is necessary for the stators of repulsion-type motors. The winding on the *rotor* of repulsion-start and repulsion motors is the same as that used on d-c armatures,† while the rotor on a repulsion-induction machine has both a d-c armature winding in an outer set of slots and a squirrel cage in another set of slots directly below.

As illustrated by Figs. 16 and 17, there are generally two ways of arranging the coils in the stator slots for a spiral or skein winding; they differ only in the spread of each pole group. In one arrangement, Fig. 16, each pole group of coils occupies its own set of slots, and there is no overlapping of the outer coil-sides of adjacent pole groups; in the second, Fig. 17, the slots

* The speeds listed are 60-cycle synchronous speeds. Actual speeds for induction motors are slightly less than those given.

† SISKIND, C. S., "Direct-current Armature Windings," McGraw-Hill Book Company, Inc.

into which the outer coils are placed contain two coil-sides from adjacent pole groups.

When the 36-slot stator is used for a four-pole winding, the two possibilities may be represented by the simplified sketches of Fig. 22. In the first arrangement, Fig. 22*a*, each pole group of four coils spans *eight* teeth, and the inner coils surround one vacant slot and two teeth; in the second

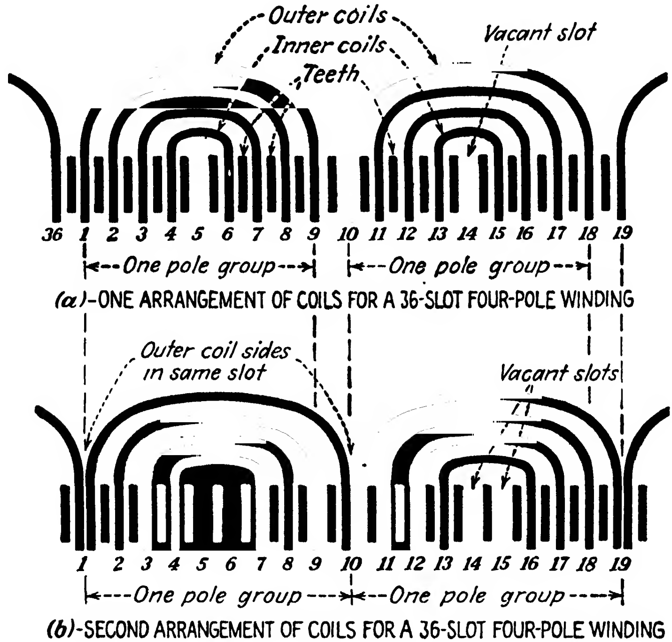


FIG. 22. Two arrangements of coil groups for a spiral or skein winding. Only two of the four groups are shown in each case.

arrangement, Fig. 22*b*, each pole group of four coils spans *nine* teeth, and the inner coils surround two vacant slots and three teeth. Note also in the latter sketch that slots 1, 10, 19, and 28 (not shown) contain two coil-sides, each one from the outer coils of adjacent pole groups. In some designs in which there are only three coils in each pole group, the inner, or smallest, coils of Fig. 22 are omitted; in such arrangements, therefore, the inner coils surround four and five teeth, respectively.

A complete skein winding diagram for a 36-slot 4-pole repulsion-type motor is shown in Fig. 23. The heavy lines represent many wires of a skein bundle. In studying the winding carefully, the following points are of particular significance: (1) Each pole group contains three coils surrounding three vacant slots and four inner teeth; (2) the first skein is started in slots 3 and 7 outward (away from the winder in the actual machine), while

the second, third, and fourth skeins are started outward in slots 12 and 16, 21 and 25, and 30 and 34, respectively; (3) the first (inner) and third (outer) coils of each pole group are looped through the slots once, while the middle coils are looped through the slots twice; (4) the slots in which the inner and

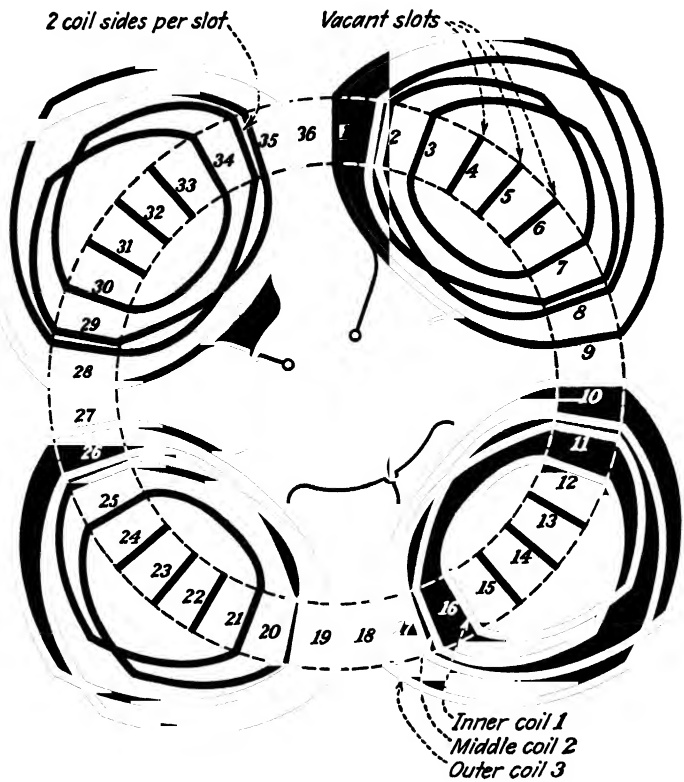


FIG. 23. Skein winding for 36-slot four-pole repulsion-type motor. Note that the middle coils of the pole groups are looped twice through the slots 2, 8, 11, 17, 20, 26, 29, and 35.

outer coils of each pole group are placed contain single bundles of wires, while those slots in which the skein is looped through twice contain two bundles of wires — note that slots 2 and 8, 11 and 17, 20 and 26, and 29 and 35 have double bundles; (5) the four pole groups are connected in series, so that successive groups always carry currents in opposite directions, *i.e.*, clockwise and counterclockwise. If, for example, each skein were wound with 20 turns of wire, the inner and outer coils of all pole groups would have 20 turns each, while the middle coils would each have the equivalent of 40 turns.

Figure 24 shows a second arrangement of coils in a winding for a 36-slot 4-pole repulsion-type motor. With proper design this complete concentric form of winding is, for all practical purposes, electrically similar to that illustrated by the skein winding of Fig. 23. Several important construc-

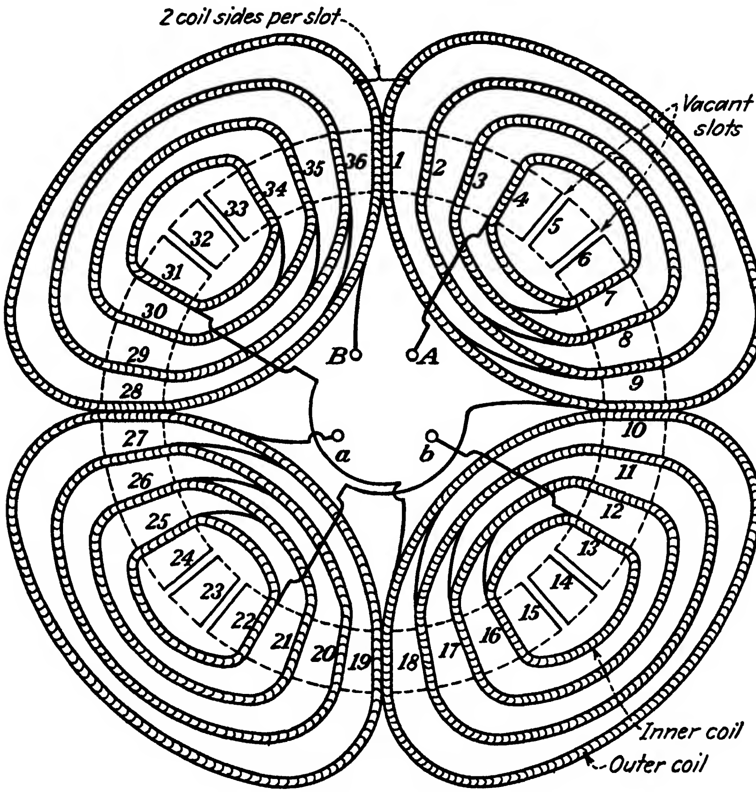


FIG. 24. Concentric winding for a 36-slot four-pole repulsion-type motor with four leads brought out so that the machine can be connected for 115- or 230-volt operation. For 230 volts, connect *a* to *B* and use *A* and *b* as line leads. For 115 volts, join *A* to *B* and join *a* to *b*; then use the junction points as line leads.

tional differences should, however, be noted: (1) There are four concentrically formed coils in each pole group (three could have been used); (2) the inner coils of each pole group surround two vacant slots and three teeth; (3) there are two coil-sides in each of the slots into which the outer coils are placed—note slots 1, 10, 19, and 28. A photograph of a completely wound stator illustrating the concentric type of winding, here discussed, is shown in Fig. 25. Clearly seen are the concentrically shaped coils and the slot wedges holding the coils in place in the slots.

It should now be pointed out that, although the skein and concentric windings are electrically similar, the concentric arrangement of coils lends itself to somewhat better design and therefore superior motor performance. The reason for this is that each one of the concentric coils in any pole group can be wound with the *proper* number of turns, determined by well-known

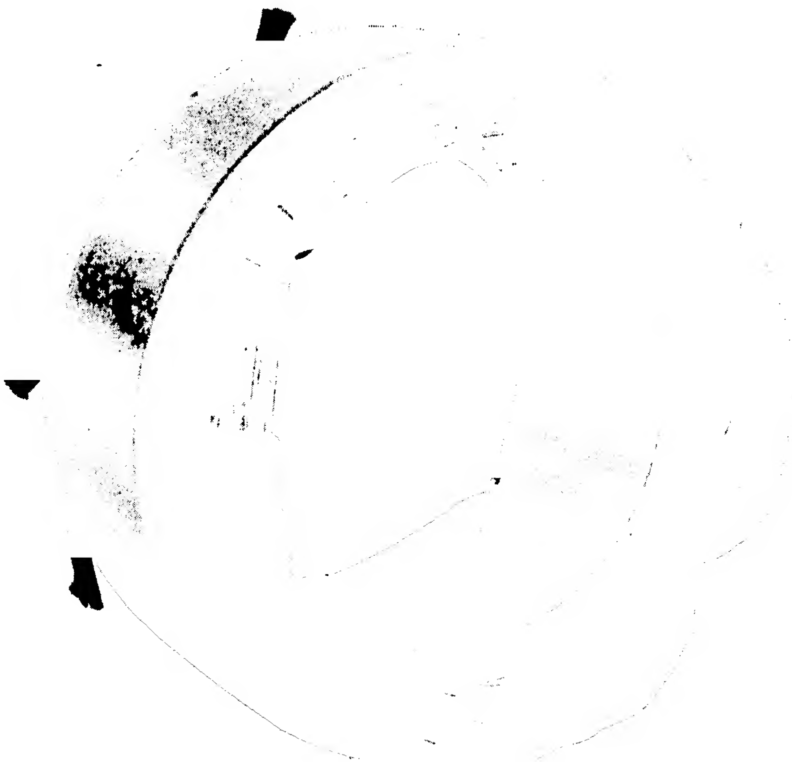


FIG. 25. Completely wound four-pole stator of a repulsion-type motor. (*Wagner Electric Corp.*)

design procedures. This is not true of skein windings where the number of turns in the various coils are definite multiples of the skein bundle. For example, in the concentric winding there might correctly be a total of 112 turns in a four-coil pole group divided into 16, 31, 42, and 23 turns in the individual coils, inside to outside, respectively. On the other hand, the best approximation that a skein winding could have, with a total of 112 turns in a three-coil pole group, is a 28-turn skein in which the inner and outer coils have 28 turns each, and the middle coil, with a doubled-back

skein, has 56 turns. As a rule, however, the operating motor advantage that results by using the concentric winding is offset by the lower manufacturing cost of the skein-wound machine.

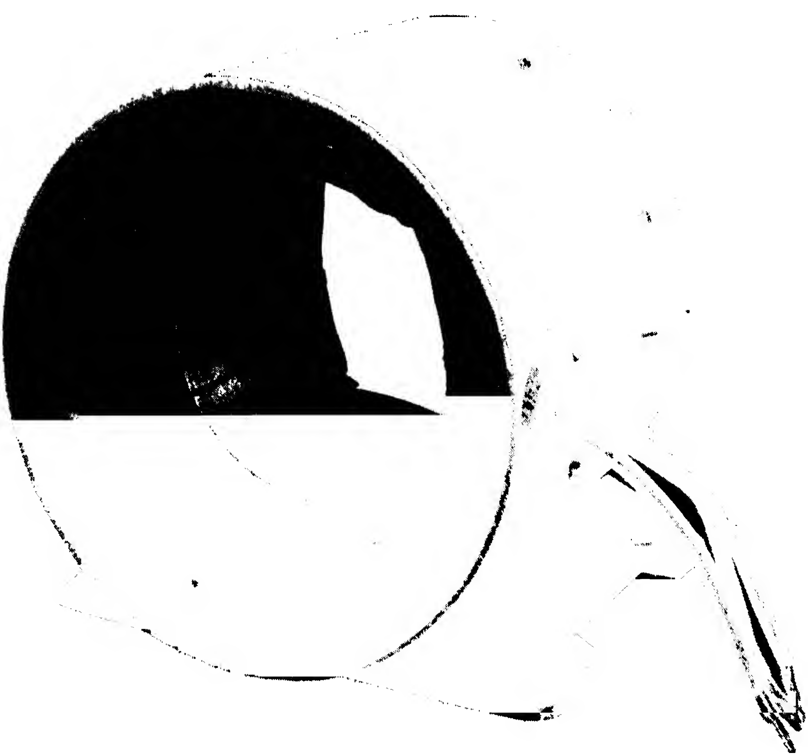


FIG. 26. Completely wound four-pole stator showing four leads brought out for operation on 230 or 115 volts. (*Wagner Electric Corp.*)

Windings for Two Operating Voltages

It is frequently desirable to manufacture motors so that they may be connected to either of two common a-c voltages, *i.e.*, 115 volts and 230 volts. This is very simply accomplished by designing the winding so that when all pole groups are connected in series the motor is used with the 230-volt source. If the same winding is then connected in two parallel sections it can be served by a 115-volt source. *In both cases the voltage per pole group is exactly the same,* since 230 volts divided by all of the pole groups in series (for example, 230/4) is the same as 115 volts divided by half the pole groups (115/2 for the same example).

Figure 24 illustrates how the leads are brought out in a four-pole 230/115-volt motor. Note that opposite pole groups *only* are connected in series; leads A and a are the ends of two series pole groups, and leads B and b are the ends of the other two series pole groups. Thus, if a and B are joined together, the winding will be connected for 230 volts; successive coil groups will, of course, carry currents in opposite directions. Moreover, if A is joined to B, and a is joined to b, the junction points may be connected to a

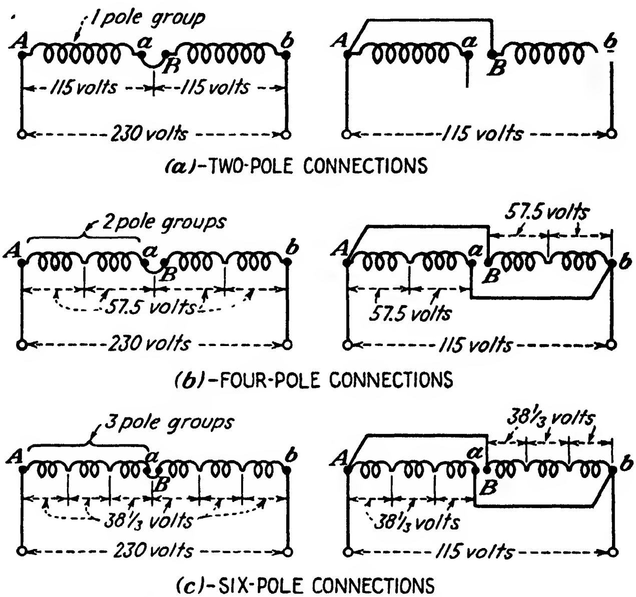


FIG. 27. Schematic wiring diagrams showing how two-, four-, and six-pole windings are connected for 230- and 115-volt operation.

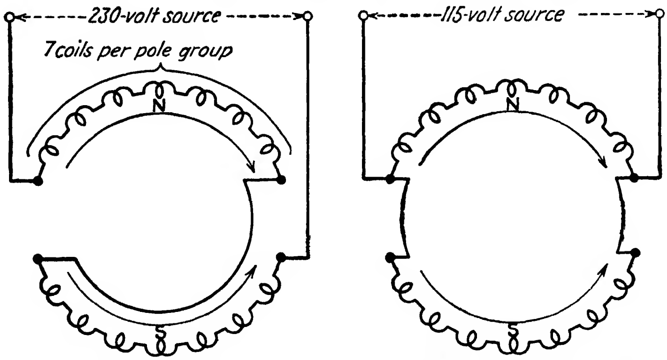
115-volt source; here again successive coil groups always carry currents in opposite directions. A photograph showing a dual-voltage stator for a repulsion motor is depicted in Fig. 26. The four leads brought out through the sides of the frame may be connected for operation on either 230 or 115 volts.

Figure 27 illustrates schematically how two-, four-, and six-pole motors should be connected for 230- and 115-volt operation. Note particularly that in each pole combination the voltage across each pole group is the same.

Simplified Diagrams of Concentric or Skein Windings

Completely developed diagrams like those illustrated in Figs. 23 and 24 emphasize constructional details that are basic to an understanding of single-phase winding practice. However, as soon as the principles and the

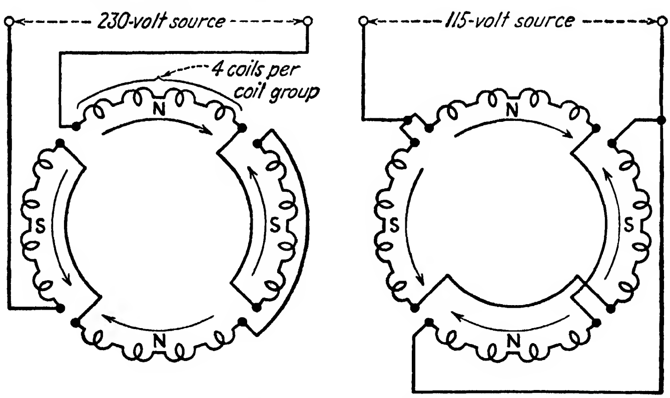
techniques of such windings are mastered, it is no longer necessary to show them in this elaborate way; simpler diagrams that are just as effective and easier to read may be drawn to represent the many variations that are



(a)-SERIES CONNECTION (b)-TWO-PARALLEL CONNECTION

FIG. 28. Simplified winding diagrams for a two-pole repulsion-type motor.

employed on modern machines. The simplified winding diagrams that follow have been made in this way; when studied for their broader meanings, therefore, it should be understood that they attempt to simulate concentric or skein type of construction.



(a)-SERIES CONNECTION (b)-TWO-PARALLEL CONNECTION

FIG. 29. Simplified winding diagrams for a four-pole repulsion-type motor.

Figure 28 illustrates a two-pole winding diagram in which there are seven coils in each pole group. Note that the arrows are drawn to indicate an assumed instantaneous direction of current flow so that a *north* (clockwise) and a *south* (counterclockwise) pole are created. Figure 28*a* shows the *series*, 230-volt connection, while Fig. 28*b* is the *two-parallel* connection for 115-volt service.

Figure 29 represents a four-pole winding diagram in which there are four coils in each pole group (similar to that of Fig. 24). Here again the connections are made so that successive pole groups create opposite polarities at any time instant; note that the arrows are arbitrarily drawn to indicate *north* (clockwise) and *south* (counterclockwise) poles.

A winding diagram for a six-pole motor is shown in Fig. 30. Each pole group is seen to have four coils and is properly indicated as carrying current for the proper (*north* or *south*) polarity. A common procedure is to bring out four leads so that the winding may be connected for 230-volt (series) or 115-volt (two-parallel) service. This is done here as it was in Fig. 24.

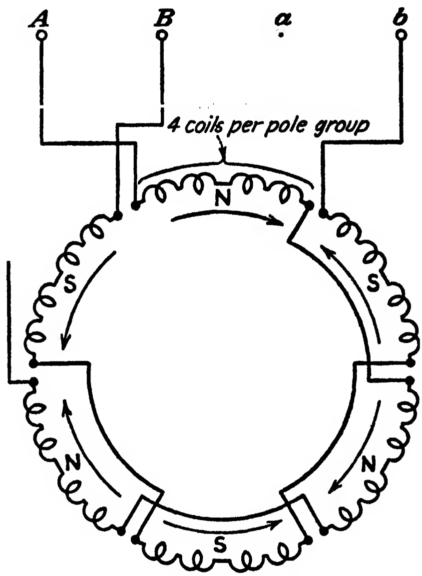


FIG. 30. Simplified winding diagram for a six-pole repulsion-type motor, with four leads brought out so that machine can be operated from a 230- or 115-volt source. For 230 volts, join *B* to *a* and connect *A* and *b* to line terminals. For 115 volts, connect the junction of *A* and *B* to one line terminal, and the junction of *a* and *b* to the other line terminal.

Reversing Repulsion Motors

Repulsion-type motors have a set of short-circuited brushes that rest on the commutator of the revolving rotor. The position of the brushes with respect to the stator winding determines the direction of rotation of the rotor. As a rule, there are two etched marks on one of the end bells of the motor that indicate the best positions to which a pointer, fastened to the brushes, should be moved for one or the other directions of rotation. To move the brushes so that the pointer lines up with one or the other indications, a set screw must be loosened; after the brushes are moved to the desired position, the set screw must be tightened. If the brushes are moved so that the pointer is on the *left* mark, the rotor will turn counterclockwise; if it is on the *right* mark, clockwise rotation will result. In some special applications of repulsion motors, the brushes may be moved to either position by the operation of a foot treadle so that the motor may be made to rotate clockwise or counterclockwise as desired.

The important point to remember is that repulsion-type motors cannot be reversed by changing winding connections or interchanging line terminals.

Summary

1. Spiral and skein windings are used in several types of single-phase motor.

2. There are three general constructions of the repulsion type of motor; these are called repulsion-start, repulsion, and repulsion-induction, according to the manner in which the brush mechanism operates and the rotor winding or windings are arranged.

3. A number of variations of the concentric or skein windings are used in the design of single-phase motors.

4. The number of slots in the stators of repulsion-type motors depends upon (1) the number of poles for which the machine is wound and (2) the size of the motor.

5. The 36-slot stator lamination is the most generally used for single-phase motor service because (1) it can be efficiently wound for two-, four-, and six-pole operation and (2) it provides the most satisfactory number of slots for use in 1/6-, 1/4-, and 1/3-hp motors, the sizes that are manufactured in the greatest numbers.

6. Only one complete concentric or skein winding is necessary for the stator of a repulsion-type motor.

7. The rotor of the repulsion-type motor has a d-c armature winding, and in some cases an additional squirrel cage.

8. There are two general variations of the concentric or spiral winding; they differ from each other only in the spread of each pole group.

9. In one pole group arrangement of coils, the latter occupy their own set of slots; in the second arrangement, the slots into which the outer coils are placed contain two coil-sides from adjacent pole groups.

10. Concentric and skein windings, although electrically similar, differ in their ability to provide equivalent motor performance in machines that are otherwise identical.

11. The concentric winding can be designed so that each coil in a pole group has the proper number of turns for best motor performance.

12. The skein winding must be designed so that the number of turns in the various coils of a pole group are definite multiples of the skein bundle. This procedure makes it necessary to use an approximation of the best turn arrangement.

13. Windings are frequently designed so that they may be connected for either 230- or 115-volt operation.

14. For 230-volt service, windings are generally connected with all pole groups in series; for 115-volt service, the same windings are connected in two parallel groups.

15. It is important to understand that the voltage across each pole group

in a given motor winding must be the same for 230-volt or 115-volt operation.

16. Adjacent pole groups must be connected so that opposite polarities are produced at any time instant.

17. Windings are frequently designed so that four leads are brought out in order that they may be connected externally for 230- or 115-volt service.

18. Repulsion-type motors have a set of short-circuited brushes that rest on the commutator of the revolving rotor. The position of the brushes with respect to the stator winding determines the direction of rotation of the rotor.

19. Repulsion-type motors cannot be reversed by changing winding connections or by interchanging line terminals.

CHAPTER 5

Windings for Split-phase Motors

The *split-phase* type of motor is used in greater numbers than any other connected to single-phase sources of supply. It is generally manufactured in fractional-horsepower sizes and many styles, offering the user of such machines a choice of a number of desirable operating characteristics. Several constructions are available, namely, (1) straight split-phase motors, (2) those that employ a capacitor during the starting period only, (3) those making use of one capacitor during the starting period and another for running duty, and (4) others in which the same capacitor is kept in service continuously. In all, however, the same winding arrangement is commonly used; this is a combination of two concentric or skein windings that are displaced on the stator core 90 electrical degrees from each other. It will be the purpose of this chapter to discuss such windings.

Main and Auxiliary Windings

Unlike the rotor of a repulsion-type motor, which has a d-c armature winding and a commutator, the split-phase motor rotor always employs the squirrel-cage construction. And, whereas the starting ability (starting torque) of the repulsion type is developed because of the rotor winding and a set of short-circuited brushes that are properly located on the commutator, starting torque in the split-phase motor can result only if a second winding is placed in the same stator slots that already contain the one discussed in Chap. 4. Therefore, for starting-torque purposes only, it is as though the second winding, in the stator of the split-phase motor, replaces the d-c armature winding on the rotor and its accompanying short-circuited brushes in the repulsion-type motor.

The second winding referred to in the foregoing paragraph is called the *auxiliary winding.* It is identical with any of the concentric or skein windings already discussed and is connected to the very same source of supply that serves the first winding; *i.e.*, the two windings are in parallel with each other. To distinguish the auxiliary winding from the first winding, the latter is designated the *main winding.* In general, the main winding has more coils and turns per pole group and is wound with a heavier wire than the auxiliary winding. The two windings must always be located in

the stator core so that they are displaced from each other in space by 90 electrical degrees.

By means of simplified sketches similar to those of Figs. 28 and 29, the relative positions of the main and auxiliary windings are shown, in Fig. 31, for a two-pole and a four-pole motor. The connections between pole groups have been purposely omitted so that the 90-electrical-degree phase displacement between windings may be emphasized. Note also that the

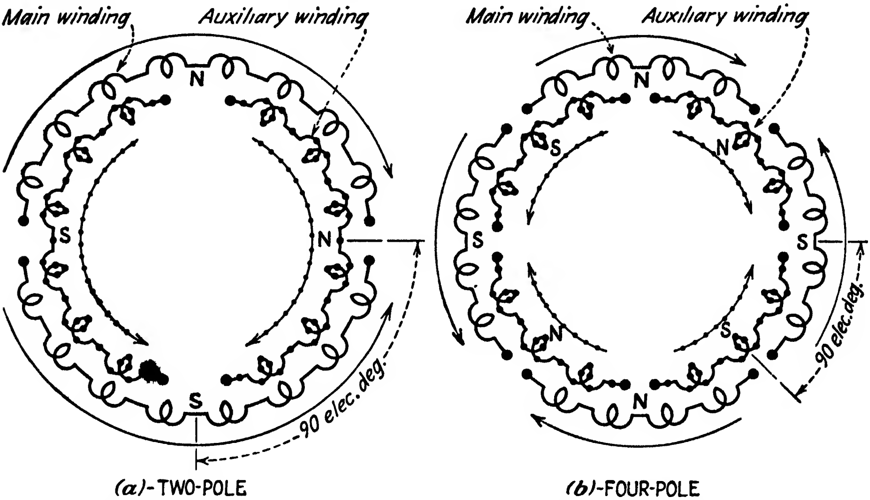


FIG. 31. Sketches illustrating the arrangement of the main and auxiliary windings in split-phase motors.

main winding is shown with a continuous line, while the auxiliary winding is drawn with a dotted full line.

In the actual split-phase motor, the main winding is put into the stator core first, so that it occupies the bottoms of the slots; the auxiliary winding is then placed on top of the main winding, carefully insulated from it, of course, so that it is near the inside cylindrical surface of the stator.

Uses of Auxiliary Windings

The most common use of the auxiliary winding in split-phase motors is to aid the main winding in its function to develop starting torque; the main winding operating by itself cannot do so. After the rotor reaches approximately 75 per cent of normal speed [see Eq. (3), Chap. 2], the main winding alone will develop nearly as much torque as both windings acting together. When the rotor speed becomes the rated value, the torque developed with both windings in the circuit is less than when only the main winding is energized. It seems logical, therefore, to provide some sort of mechanism,

actuated by a centrifugal device, or an electromagnetic relay, that will cut out the auxiliary winding at the proper instant. Many such mechanisms have been developed. In the common applications of this motor, designated a *straight split-phase motor*, centrifugally operated governors are

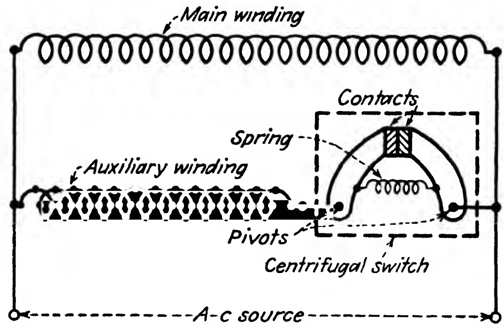


FIG. 32. Wiring diagram showing how the main and auxiliary windings and the centrifugal switch are connected in a straight split-phase motor.

employed wherein a set of spring-loaded weights, mounted on the shaft, fly out at a predetermined speed; in the process a switch mechanism fastened to the end bell disconnects the auxiliary winding from the circuit. Figure 32 is a schematic wiring diagram illustrating the connections of the

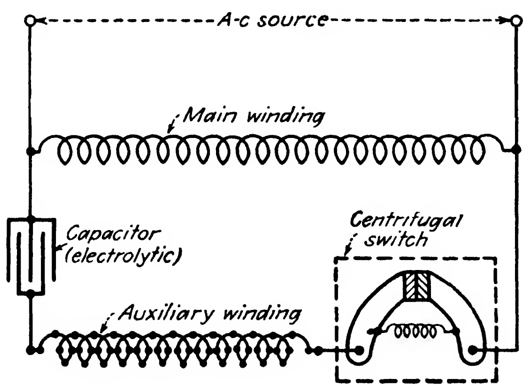


FIG. 33. Wiring diagram showing how the main and auxiliary windings, the centrifugal switch, and the capacitor are connected in a capacitor-start split-phase motor.

main and auxiliary windings and a simple centrifugally operated switch. When the speed of the rotor is at any value that requires both windings in the circuit, the spring tension is greater than the centrifugal forces exerted by the pivoted weights; the switch contacts are therefore closed and the auxiliary winding is energized. At the proper rotor speed, the

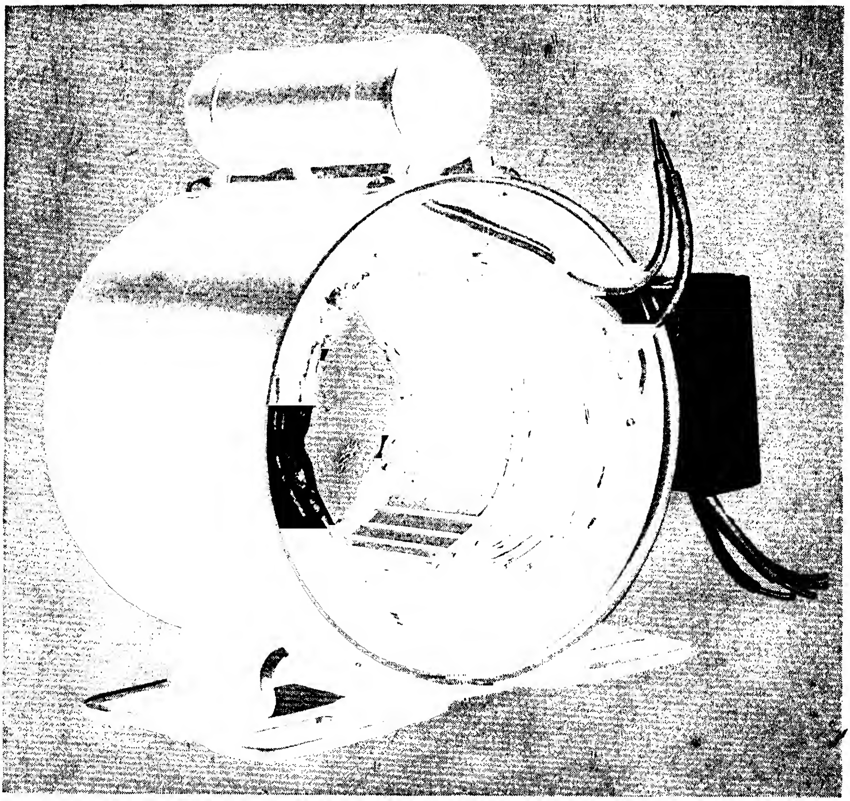


Fig. 34. Stator of a capacitor-start split-phase motor with the electrolytic capacitor mounted on top. (*Wagner Electric Corp.*)

centrifugal forces exerted by the weights are greater than the spring tension; under this condition the contacts open and the auxiliary winding is disconnected from the source of supply.

In some applications of the split-phase motor, the required starting torque must be much greater than that developed by the straight split-phase motor. By connecting a capacitor of the proper value in series in the auxiliary winding circuit, the motor may be made to have two to four times as much starting torque as one without capacitors. Such machines are called *capacitor-start split-phase motors.* A wiring diagram illustrating the manner in which the capacitor is inserted is shown in Fig. 33. In practice the centrifugally operated switch cuts out the auxiliary winding at the same speed as it would in the straight split-phase motor. With the auxiliary winding disconnected, the motor continues to operate like a normal straight split-phase motor. Figure 34 illustrates a stator of a

capacitor-start split-phase motor, with an electrolytic-type capacitor mounted on the top of the frame. When the machine is ready for assembly, the two upper leads would be connected to the centrifugal switch; the four leads shown coming out of the junction box at the left may be connected so that the machine may be operated from a 230- or a 115-volt source.

In order to utilize the auxiliary winding during the running as well as the starting period, it is necessary to have two capacitors and a special centrifugal switch. During the starting period, a SPDT centrifugal switch connects a high-value electrolytic capacitor in the auxiliary winding circuit.

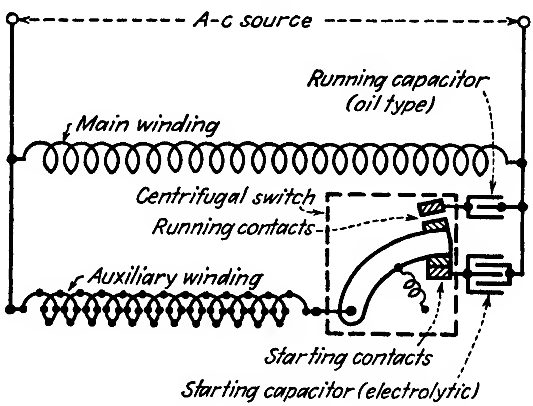


FIG. 35. Wiring diagram showing the connections for a two-value capacitor split-phase motor.

At the proper predetermined speed the *starting* contacts open and the *running* contacts close; in the process the high-value short-duty electrolytic capacitor is disconnected from, and a low-value continuous-duty oil-type capacitor is connected into the auxiliary winding circuit. Figure 35 illustrates schematically how this is accomplished. Such machines, designated *two-value capacitor split-phase motors,* have superior starting and running characteristics, good efficiency and power factor, and are extremely quiet in operation. They do, indeed, approach the operating performance of two-phase induction motors, which they are intended to simulate.

Still another variation of the split-phase motor dispenses with the centrifugal switch entirely and employs a continuous-duty oil-type capacitor in the auxiliary winding circuit. The purpose of such construction is to imitate the running characteristics of the two-phase motor without attempting to develop a comparatively high starting torque; in order to accomplish the latter, a much higher value of capacitance must be used during the starting period than the one suitable for the running condition. (As was pointed out in the foregoing paragraph, the two-value capacitor motor

develops high starting torque as well as good running performance.) *Permanent capacitor split-phase motors,* which these are called, are generally made in rather small sizes. They are used mostly in installations where very quiet operation is extremely important. A wiring diagram showing the connections in this motor is shown in Fig. 36.

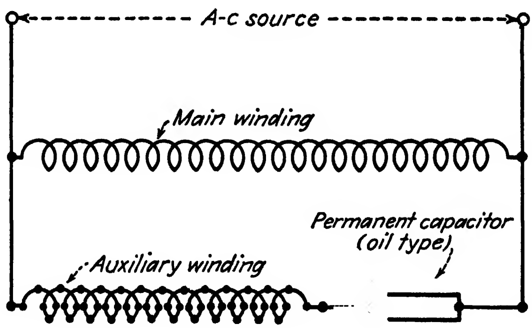


FIG. 36. Wiring diagram showing the connections for a permanent capacitor split-phase motor.

Laying Out Windings for Split-phase Motor Stators

If a split-phase type of motor is to develop starting torque, its stator must have both a main winding and an auxiliary winding; this is true whether or not there is a capacitor or centrifugal switch in series with the auxiliary winding. To simplify the winding diagrams that follow, therefore, capacitors and centrifugal switches are omitted, but it is to be assumed that these would or would not be included as the type of motor previously discussed demands. It is further assumed that either the concentric or skein form of winding is used.

An extremely common split-phase motor stator is one having 36 slots and wound for four poles. As previously pointed out (see Figs. 23 and 24), two arrangements of coils are used. In some constructions, the overlapping coils are employed in both main and auxiliary windings. In others, there is a distinct separation of pole groups (Fig. 23), while in still others, one style is used for the main winding and the other for the auxiliary winding. Figure 37 illustrates a complete winding diagram for the previously mentioned numbers of slots and poles. The pole groups of both main and auxiliary windings are shown connected in series. It will be noted that the main winding (on the outside and represented with a continuous line) has four coils per pole group; it is of the overlapping style, where slots 1, 10, 19, and 28 each have two coil-sides per slot. Each of the pole groups of the auxiliary winding (on the inside and represented with a *dotted* con-

tinuous line) has three coils per pole group, and there is a distinct separation between pole groups. This diagram should be studied very carefully since it typifies much of the foregoing discussion concerning split-phase motor windings, as well as many others that follow.

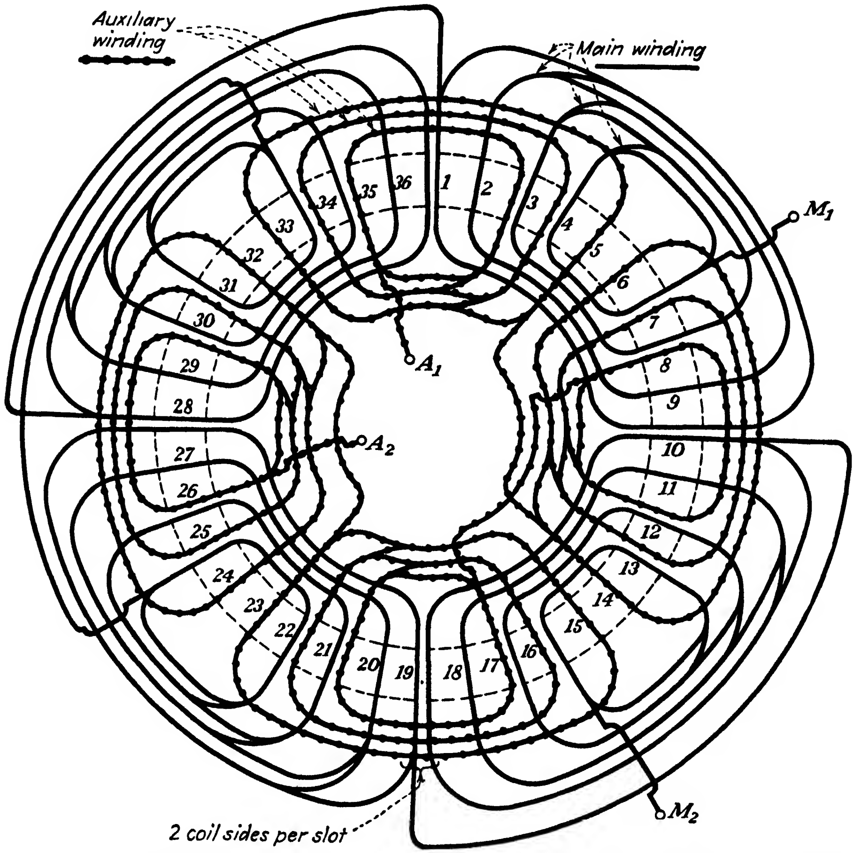


FIG. 37. Complete winding diagram for a 36-slot four-pole split-phase motor stator.

Bearing Fig. 37 in mind, a number of simplified winding diagrams will now be given to represent several combinations of slots and poles. In each case explanatory notes will emphasize important and significant items.

Figure 38 illustrates a skein winding for a 24-slot two-pole motor. This diagram has been laid out straight for simplicity and may be readily compared with the more complete drawing if the following points are noted: (1) The upper portion represents the main winding (continuous line); (2) the lower portion represents the auxiliary winding (*dotted* continuous line); (3) there are five coils in each pole group in both the main and

auxiliary windings; (4) pole groups of main and auxiliary windings are connected in series; (5) overlapping coil constructions are used in both windings; (6) the skein type of winding is indicated because the numbers

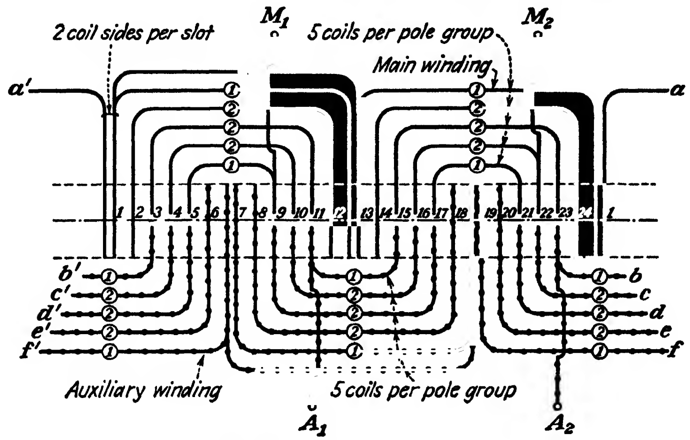


FIG. 38. Simplified skein winding for a 24-slot two-pole stator of a split-phase motor. The pole groups in both main and auxiliary windings are connected in series.

1 and 2 in each coil represent the number of times the skein is looped through the corresponding slots.

Figure 39 illustrates a concentric winding for a 48-slot six-pole motor

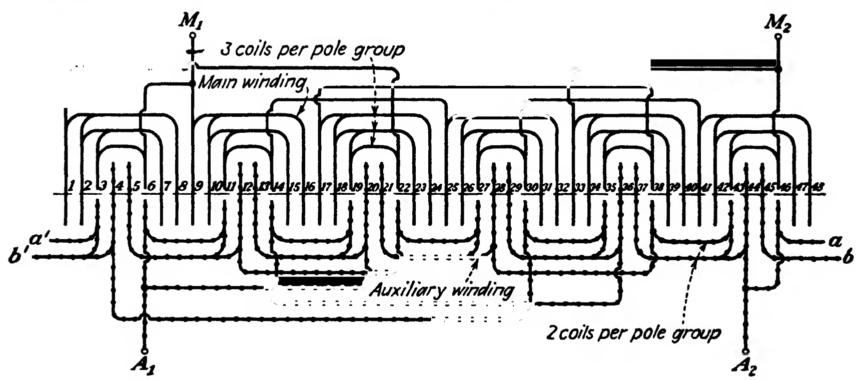


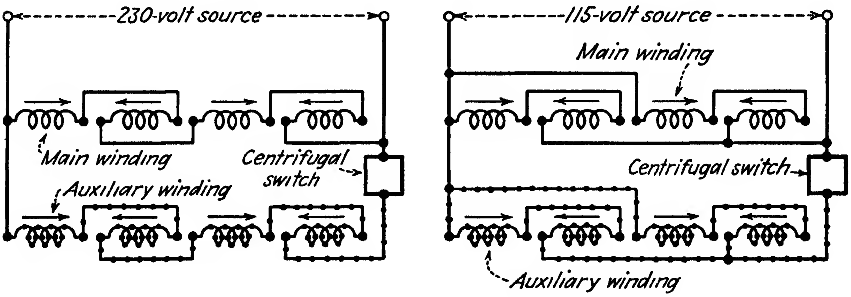
FIG. 39. Simplified concentric winding for a 48-slot six-pole stator of a split-phase motor. The pole groups in both main and auxiliary windings are connected in two parallel paths.

in connection with which the following points should be noted: (1) There are three coils per pole group in the main winding and two coils per pole group in the auxiliary winding; (2) this is called a *two-parallel* winding because both main and auxiliary windings are connected so that there are

two parallel paths in each; (3) there is no overlapping of pole groups in either main or auxiliary winding, since each pole group occupies its own set of eight slots; (4) the concentric type of winding is indicated because the individual coils in each pole group are shown connected together.

Split-phase Motor Windings for Two Operating Voltages

It was pointed out in Chap. 4 that repulsion-type motors can be designed for either of two operating voltages, *i.e.*, 230 volts or 115 volts. The same principles apply equally well to split-phase motor windings, with the added requirement that both main and auxiliary sections must be treated simi-



(a)-SERIES CONNECTION (b)-TWO-PARALLEL CONNECTION

FIG. 40. Schematic wiring diagrams showing how a split-phase motor winding is connected for 230- or 115-volt service.

larly. In general, where the 230-volt connection is desired, the pole groups of each of the main and auxiliary windings are joined in series (see Fig. 38); if the motor is to be used on a 115-volt service, the two-parallel connection must be employed (see Fig. 39). Schematic wiring diagrams, Fig. 40, illustrate how the connections must be made for a four-pole motor. When the two-parallel connection is used for windings having more than four poles, it is, of course, necessary to join together properly one-half of the pole groups in series for each of the parallel paths.

Reversing Split-phase Motors

The direction of rotation of a split-phase motor depends upon the manner in which the auxiliary winding is connected with respect to the main winding. Remembering that the main and auxiliary windings are always in parallel with each other, it should be clear that there are two possibilities when making this connection. Referring to Figs. 37, 38, and 39, one direction of rotation will result if the junction of M_1 and A_1 is connected to one line terminal and if the junction of M_2 and A_2 is connected to the other line terminal. The motor will revolve in the opposite direction, in each case,

if the junction of M_1 and A_2 is connected to one line terminal and if the junction of M_2 and A_2 is connected to the other line terminal. The motor will not reverse if the line terminals are merely interchanged.

A schematic wiring diagram showing how a four-pole split-phase motor is reversed is represented by Fig. 41.

If it is desired to predetermine the direction in which a split-phase motor will rotate, the following rule should be applied: **Rotation will always take place from a given magnetic polarity of an auxiliary winding**

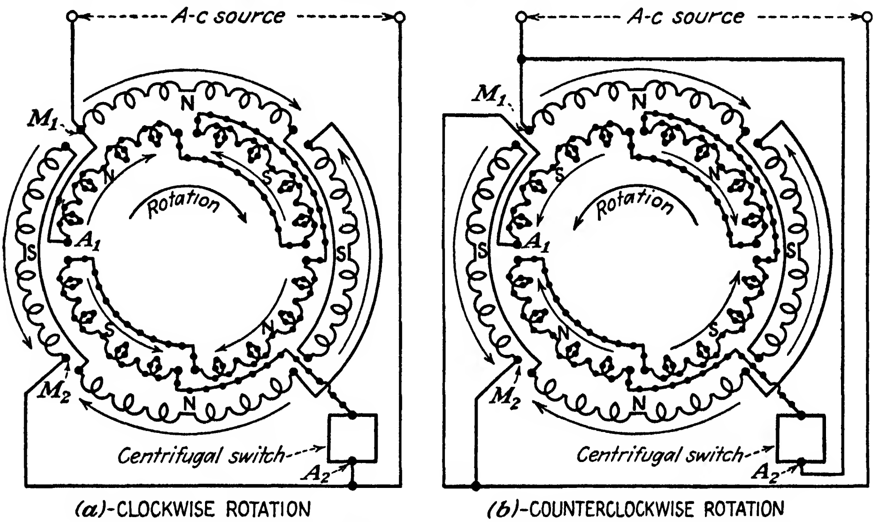


FIG. 41. Wiring diagrams showing how a split-phase motor is connected to rotate in either direction.

pole to the same magnetic polarity of the next nearest main winding pole. Referring to Fig. 41*a*, note that magnetic polarities of main and auxiliary windings are indicated for clockwise rotation, where the junction of M_1 and A_1 is connected to one line terminal and where the junction of M_2 and A_2 is connected to the other line terminal. In this sketch the upper left auxiliary winding pole is *north* and the next nearest *north* main winding pole is the top one; rotation along the upper semicircle will therefore be from left to right, or clockwise. In Fig. 41*b* the auxiliary winding terminals A_1 and A_2 are interchanged with the main winding terminals, so that the junction of M_1 and A_2 is connected to one line terminal and the junction of M_2 and A_1 is joined to the other line terminal. Under this condition the upper right auxiliary winding pole is *north*, while the upper main winding pole remains *north*; rotation will now be along the upper semicircle from right to left, or counterclockwise.

Applying the foregoing rule to Fig. 37, clockwise rotation will result

if the line terminals are connected to M_1A_1 and M_2A_2, respectively; the motor will rotate counterclockwise for the M_1A_2 and M_2A_1 connection.

Hand Winding and Special Equipment

In manufacturing plants where large numbers of "standard" motors are produced, special tools and equipment are generally employed in the many necessary operations; this practice minimizes the amount of costly hand work and results in reduced costs and stepped-up production schedules. Many unique and ingenious devices and machines have been developed for such purposes, although it is usually true that individual manufacturers have found it necessary to design and build their own equipment to fulfill particular requirements. In so far as winding operations are concerned, there are many styles of machines that are used to form skeins, mush coils, and involute coils, as well as numerous styles of gang molds, shuttle pullers, coil tapers, and the like. Since this phase of winding practice is beyond the scope of this book, the student is referred to special texts* and manufacturers bulletins for such information.

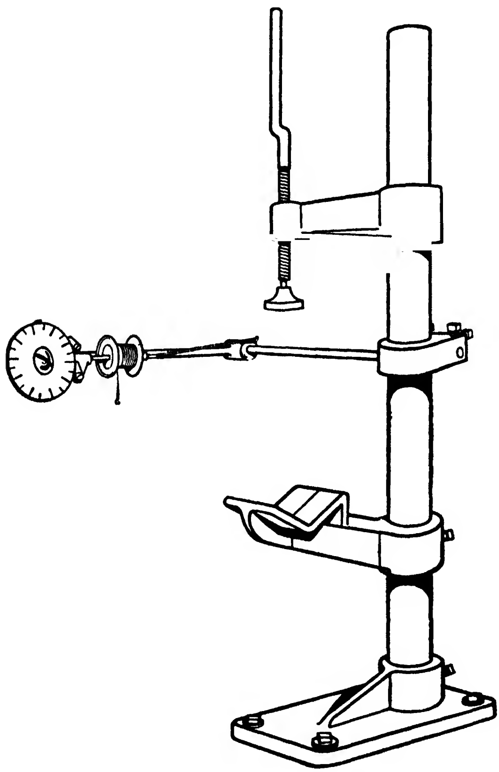


FIG. 42. Stand used for stator winding operations. Note clamping rig, wire spool, and turn counter. (*The Martindale Electric Co.*)

Repair shops are usually called upon to handle many kinds of winding and maintenance jobs and are obviously in no position to invest in expensive machinery and equipment that can be justified only on the basis of quantity production. In such places it is often necessary, therefore, to wind stators by hand or to use such special devices as may be useful in the winding of many types and styles of motors. A particularly useful construction of *hand-winding stand*

* VAN BRUNT, G. A., and A. C. ROE, "Winding Alternating-current Motor Coils," McGraw-Hill Book Company, Inc.

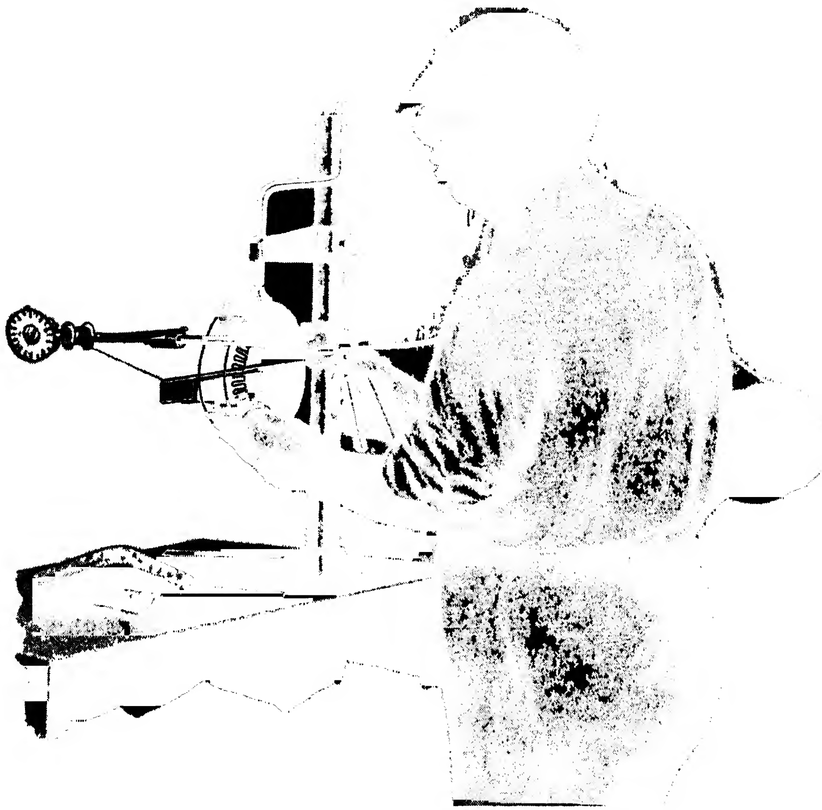


FIG. 43. Stator winding gun shown in use (*The Martindale Electric Co.*)

is shown in Fig 42. Note the clamping rig in which may be mounted many sizes of stator, the convenient location of the wire spool, and the turn counter. This device is generally employed in hand-winding stator operations where the wire is fed into the slots one at a time, an especially expensive and time-consuming practice.

When stators must be wound by threading a single wire back and forth through the slots, it is often desirable to use a *stator winding gun* similar to that shown in Fig. 43. Such a gun helps speed up production of hand-wound stators (or rotors); moreover, it serves to produce a winding job that is tighter and more uniform. To use the gun, the stator is first clamped in the vise in such a manner as to permit the left hand to move back and forth under the stator. The counter is then hooked to the muzzle of the gun by means of a string. The wire, fed from behind the operator's right side under little or no tension, is slipped through the gun from breech to

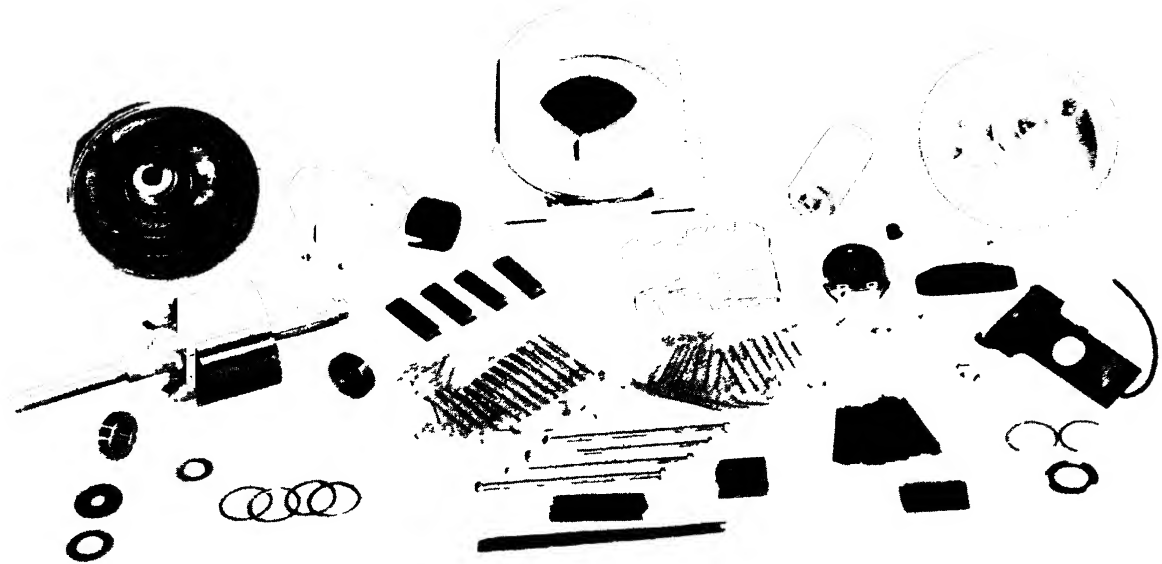


FIG. 44. Photograph showing all parts for a project involving the construction of a $\frac{1}{2}$-hp 1,725-rpm 230/115-volt capacitor-start split-phase motor. (*General Electric Co*)

muzzle. After the starting end of the wire is secured on the operator's side of the stator, the gun, with the brake released, is used to push or pull the wire through the slots. At the end of each stroke the brake is set against the wire by gripping the long trigger of the gun; while the left hand places the wire in position, the gun and the wire are given a pull to tighten the coil as it is wound. When one pole group is completed, the next one is wound in the opposite direction without cutting the wire.

Split-phase Motor Projects for School Shops

One of the most interesting and useful projects for electrical shops in vocational and trade schools is the construction of a split-phase motor.

FIG. 45 Student shown putting in auxiliary winding after completing main winding Parts for this machine are shown in Fig. 44 (*General Electric Co.*)

This involves the winding of a stator and the complete assembly of the various units such as centrifugal switch, bearings, rotor, etc. Where machine shop facilities are available, it is possible to fabricate all parts, but a more desirable arrangement for schools whose facilities and time limitations do not make this possible is to purchase well-designed kits containing everything necessary to wind a stator and assemble a motor. The parts for such a project are shown, in Fig. 44, for a 1/2-hp 1,725-rpm 230/115-volt capacitor-start split-phase motor. Clearly seen are the stator core, the rotor, end bells, bearings, centrifugal switch, capacitor, insulating materials, bolts, and miscellaneous items. When the machine is constructed in accordance with given instuctions, the student will not only have a useful motor upon its completion but will learn important electrical principles in an extremely fascinating and practical way. Figure 45 illustrates a

young student putting in the auxiliary winding after having completed the main winding.

Summary

1. Split-phase motors are generally manufactured in fractional-horsepower sizes and many styles.

2. Split-phase motors are manufactured in several constructions, referred to as (*a*) straight split-phase, (*b*) capacitor-start, (*c*) two-value capacitor, and (*d*) permanent capacitor.

3. Skein or concentric windings are commonly used to wind the stators of split-phase motors.

4. Split-phase motor stators require two concentric or skein windings that are displaced 90 electrical degrees with respect to each other. These are called (*a*) main winding and (*b*) auxiliary winding.

5. The main winding is always in service while the motor is in operation. The auxiliary winding is in continuous service in the two-value and permanent-capacitor motors; it is in service only during the short starting period in the straight and capacitor-start split-phase motors.

6. Split-phase motors always have squirrel-cage rotors.

7. Starting torque is developed in split-phase motors only because the main and auxiliary windings act together during the starting period.

8. In general, the main winding has more coils and turns per pole group and is wound with heavier wire than the auxiliary winding.

9. The main and auxiliary windings are always in parallel with each other when in operation.

10. The main winding is put in the stator core first, so that it occupies the bottoms of the slots; the auxiliary winding is placed on top of the main winding, so that it is near the inside cylindrical surface of the stator.

11. In straight and in capacitor-start split-phase motors the auxiliary winding is cut out by a centrifugally operated switch when the rotor reaches approximately 75 per cent of normal speed.

12. In two-value capacitor motors the auxiliary winding is in service continuously. There is an electrolytic-type capacitor in series with this winding during the starting period; a centrifugal switch cuts out the electrolytic capacitor and cuts in an oil-type capacitor after the motor comes up to speed.

13. Capacitor-start split-phase motors develop two to four times as much starting torque as straight split-phase motors.

14. Two-value capacitor motors have superior starting and running characteristics, good efficiency and power factor, and are extremely quiet in operation.

15. Permanent capacitor split-phase motors are generally built in rather

small sizes. They are used where the applications require comparatively low values of starting torque but where extremely quiet operation is important.

16. The 36-slot stator wound for four-pole operation is extremely common in split-phase motor construction.

17. Split-phase motors may be arranged for operation on either 230 volts or 115 volts. For 230-volt operation, the pole groups of each of the main and auxiliary windings must be changed to the two-parallel connection.

18. Split-phase motors may be reversed by interchanging the auxiliary winding leads with respect to the main winding leads.

19. The direction of rotation of a split-phase motor may be predetermined by applying the following rule: Rotation will always take place from a given magnetic polarity of an auxiliary winding pole to the same magnetic polarity of the next nearest main winding pole.

20. Special tools and equipment are generally used in the manufacture of "standard" type motors that are produced in great numbers.

21. In repair shops special devices and equipment are used only to augment the rewinding of many styles of motors, but these are generally employed in hand-winding operations.

CHAPTER 6

Two-speed Windings for Split-phase Motors

In many applications of the electric motor it is desirable, and sometimes essential, that the speed be controlled over rather wide limits. This is readily and efficiently accomplished when the drive is a d-c electric motor; in such installations, field-resistance, armature-resistance, and armature-voltage control methods are generally used to obtain smooth, and virtually stepless, speed variations. When a-c split-phase induction-type motors are used, however, it is usually difficult, expensive, and inefficient to change the speed. Moreover, variations can no longer be stepless in the sense that there are smooth speed changes over a wide range, *i.e.*, there are definite speed steps, often many rpm apart. This chapter will be concerned with several winding arrangements used to vary the speed of such machines.

Four-winding Motors for Two Speeds—Conventional

Since the normal speed of a split-phase motor depends upon the number of poles for which it is wound (for a given frequency the speed is *inversely proportional* to the number of poles), it should be clear that a motor stator that has two sets of windings (each main and auxiliary designed for a different number of poles) may be operated at one or the other of two speeds. Obviously, such a motor is physically much larger for a given horsepower and speed rating than a standard single-speed machine because it must have four windings, two mains and two auxiliaries. Depending upon the selected speed, only one set of two windings is used at a time; one set is always idle.

This *pole-changing* method is employed to a limited extent, and only when moderately good starting torque is desired for both winding combinations. In such designs the centrifugally operated switch must be made to open at the lower of the two possible speeds, the one that is somewhat below the value that is best for the higher speed winding. For example, a 60-cycle motor having winding combinations of four poles and six poles will have its centrifugal switch set to open at about 1,000 rpm; this is about 350 rpm less than is proper for the four-pole winding. A schematic wiring diagram illustrating how the four windings of a four-pole six-pole motor are connected is given in Fig. 46. Note that the centrifugal switch is

connected so that it is in series with *either* auxiliary winding when the main TPDT switch is closed to the four-pole or six-pole side. Assuming that the windings are arranged so that the direction of rotation is the same whether the motor is connected for four- or six-pole operation, the motor may be started on either speed and switched to the other speed while it is running. However, if the directions of rotation are different for the two speeds, it is necessary that the motor come to a complete stop, when operating at one speed, *before* it is switched to the other speed.

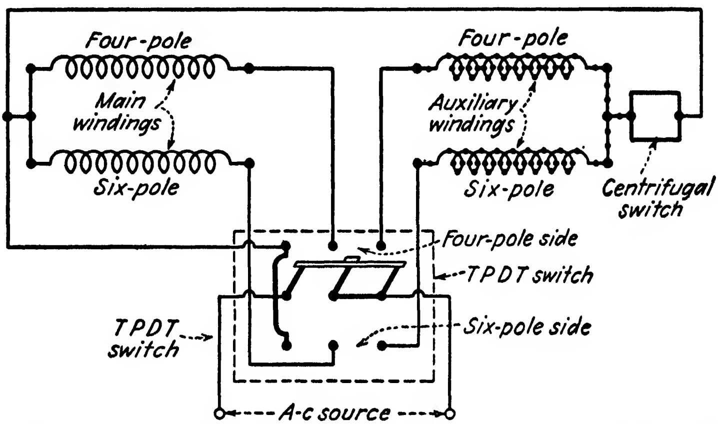


FIG. 46. Wiring diagram showing the connections for a four-winding two-speed motor.

A better understanding of the conventional manner in which the four windings are arranged in the actual stator may be gained by a study of Fig. 47. The following points should be especially recognized: (1) The auxiliary windings are displaced exactly 90 electrical degrees with respect to their respective main windings; (2) the four- and six-pole main windings are started in the same slot, *i.e.*, slot number 1; (3) to avoid confusion, the wiring from the windings to the TPDT switch have been omitted, but points *a*, *b*, *c*, *d*, and *e* on the windings have corresponding markings on the switch; (4) the pole groups of all windings are connected in series; (5) the upper and lower positions of the TPDT switch connect the windings for four-pole and six-pole operation, respectively.

Principle of Consequent-pole Windings

In the *conventional* method of connecting windings, adjacent pole groups always carry currents in opposite directions, *i.e.*, clockwise for one pole group and counterclockwise for the preceding or succeeding pole group. When this is done, the number of magnetic flux paths is exactly the same as the number of pole groups; accordingly, there are exactly as many formed

poles as magnetic flux paths. Figure 48*a* clearly illustrates how four pole groups carry currents to create four magnetic flux paths, and therefore four poles. Note that the upper and lower pole groups, carrying counterclockwise currents, create *south* poles; at the same instant, the left and right pole

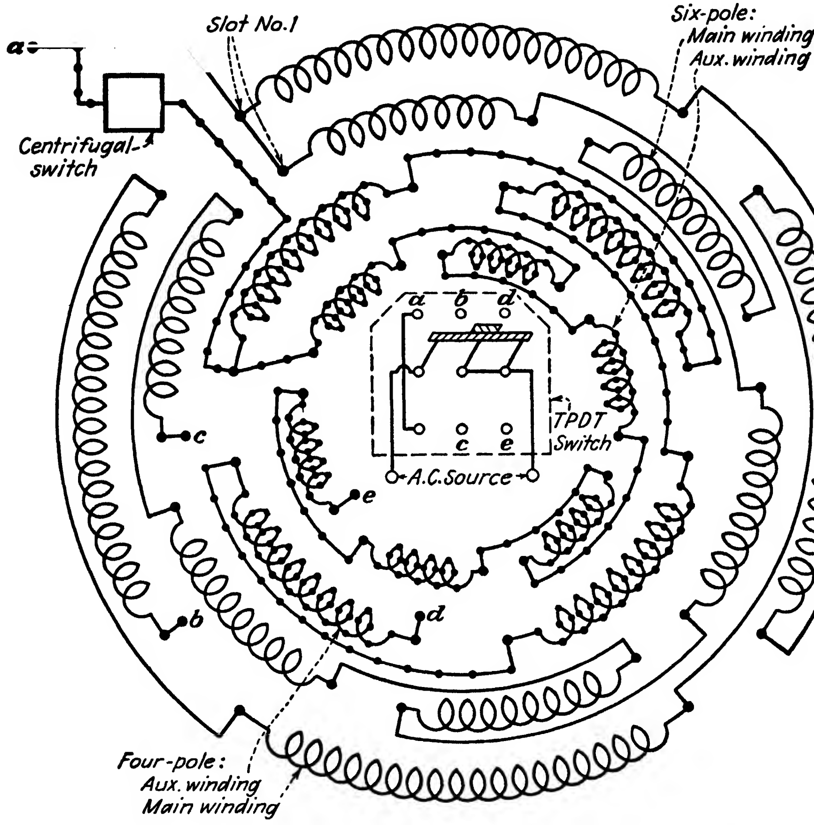


FIG. 47. Schematic four-winding diagram for a two-speed split-phase motor. Simplified wiring diagram is shown in Fig. 46, with which it should be compared.

groups carry clockwise currents and create *north* poles. (The *crosses* inside the conductors indicate currents away from the observer, and the *dots* inside the conductors indicate currents toward the observer.)

However, *if a winding is connected so that all pole groups carry currents in the same direction at any instant, there will always be twice as many magnetic flux paths as the number of pole groups*; as a result there will be twice as many formed poles as pole groups. Under this condition each magnetic flux path will, therefore, span about one-half the circumferential distance of that spanned by the conventional flux path. Moreover, the additional

poles, resulting from this manner of interconnection of pole groups, always appear exactly halfway between those that are formed by the conventionally connected winding.

Figure 48*b* shows how the currents must flow in the *four pole groups* to create *eight* magnetic flux paths, and therefore eight poles. Note particularly that, at the instant represented, (1) the currents pass through all the coils in a counterclockwise direction; (2) the top and bottom poles remain *south;* (3) the left and right poles are changed to *south;* and (4) the four

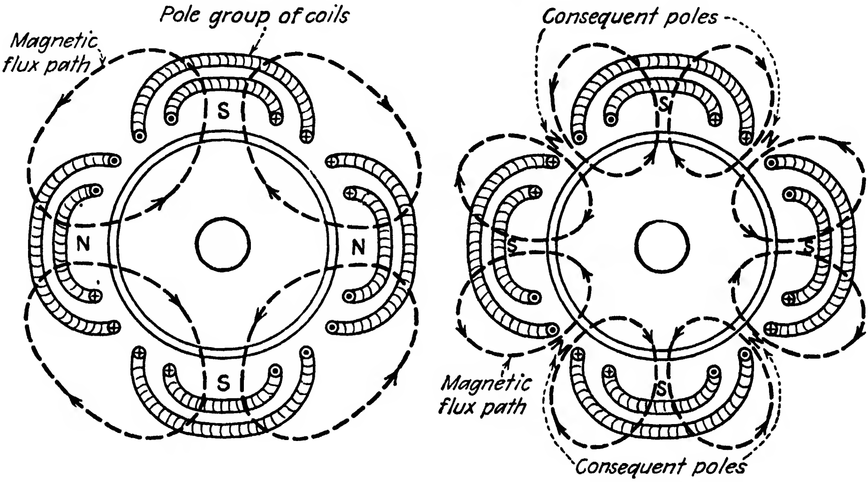


FIG. 48. Sketches illustrating a four-pole winding connected for four-pole and eight-pole operation. In the conventional connection (*a*) successive pole groups carry currents in opposite directions. In the consequent-pole connection all pole groups carry currents in the same direction.

additional poles, located between the outside coils of adjacent pole groups, are all *north.*

Since the *added poles* result as a *consequence* of the fact that all pole groups are connected to carry currents in the same direction, they are called *consequent* poles; the winding is appropriately named a *consequent-pole winding.*

In practice, one of the two mains of a two-speed motor is usually a consequent-pole winding; a consequent-pole winding may be used for one or both of the auxiliaries. As will be noted in the next section, much valuable space is saved and winding time is reduced when this is done.

Four-winding Two-speed Motors Using Consequent Poles

Figure 49 represents a diagram for a two-speed motor in which there are four windings, two mains and two auxiliaries. The outer four-pole winding

is connected in the conventional manner, with adjacent pole groups carrying current in opposite directions. The second main, for eight poles (inside the outer), is a consequent-pole winding with four pole groups. Both

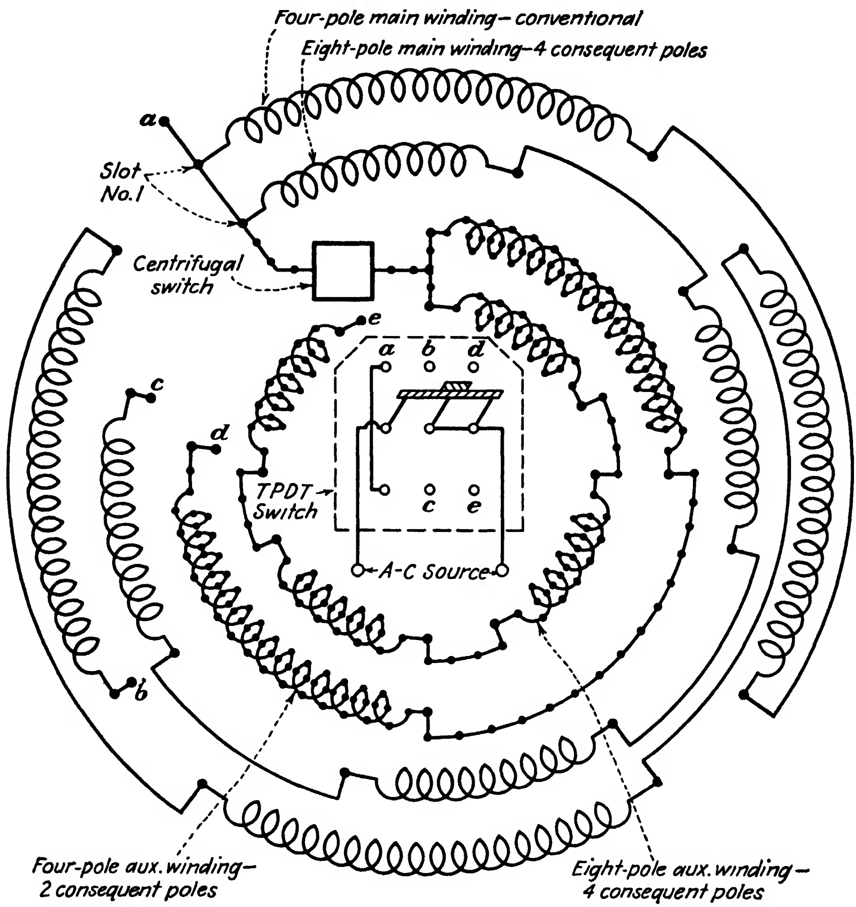


FIG. 49. Four-winding diagram for a two-speed motor. Only the outer four-pole main is a conventional winding; the other three, the eight-pole main and the two auxiliaries, are consequent-pole windings. The motor may be started by the TPDT switch on either speed.

auxiliaries are consequent-pole windings, the inner one having four pole groups for eight poles, and the other (outside the inner) being wound with two pole groups for four poles. When the TPDT switch is closed in the "up" position the motor will start and run at the higher speed; when closed in the "down" position the motor will operate at the lower speed. Note that the centrifugal switch is in series with either auxiliary when the TPDT

switch is thrown "up" or "down." Furthermore, the motor will start on either speed and can be changed, while running, to the other speed. An-

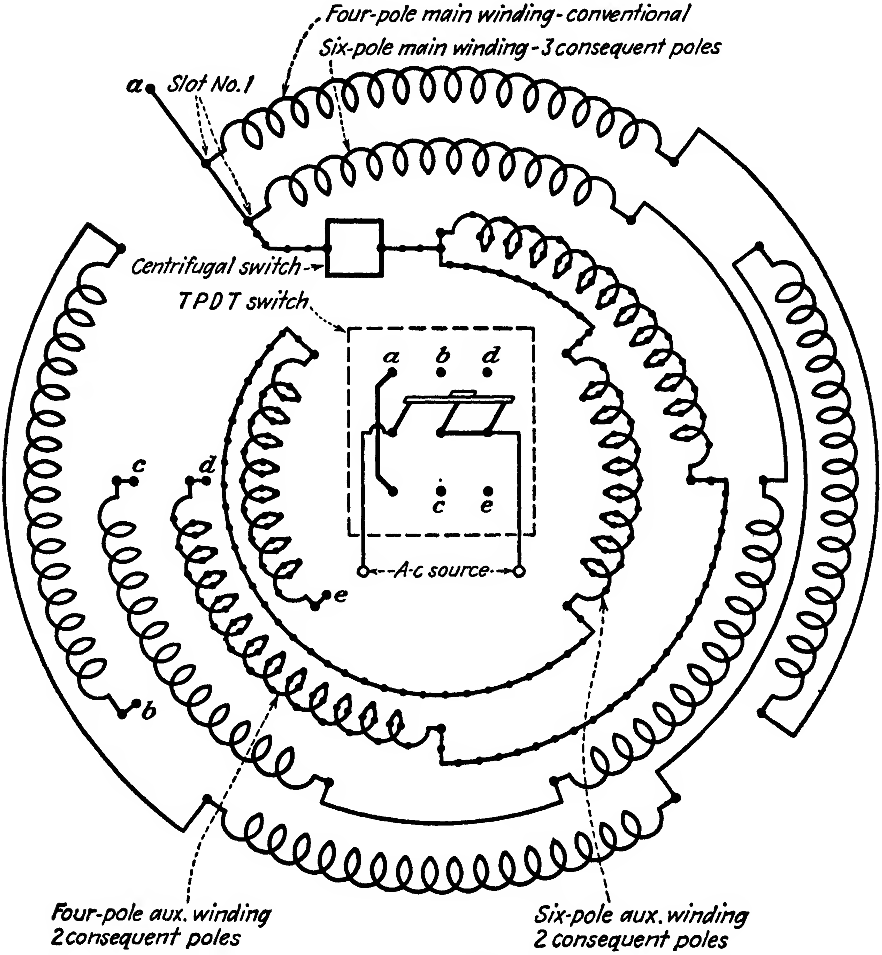


FIG. 50. Four-winding diagram for a two-speed motor. Only the outer four-pole main is a conventional winding. The second main has three pole groups and is connected as a six-pole consequent-pole winding. The inner auxiliaries are both consequent-pole windings, with two pole groups for each one of these combinations.

other important point to observe is that the auxiliaries are displaced exactly 90 electrical degrees with respect to their *respective* mains.

Figure 50 shows another diagram for a two-speed motor in which there are four windings. The outer four-pole winding is connected in the conventional manner. The second main, for six poles, is a consequent-pole winding with three pole groups. Both auxiliaries are consequent-pole

windings, with two pole groups for *each one* of the pole combinations. An interesting innovation in this diagram is that only two pole groups are used for the six-pole consequent-pole auxiliary winding. This is possible if the pole groups are located directly opposite each other on the stator and are connected to carry clockwise and counterclockwise currents respectively. The auxiliary used with the six-pole main winding actually produces only four magnetic poles, but these are formed at the proper places on the stator core for six-pole operation; it is as though two of the six poles were omitted, with a corresponding loss in starting torque. As before, the motor will start on either speed and can be changed, while running, to the other speed.

Three-winding Two-speed Motors Using Consequent Poles

To save further valuable space in the stator core, it is possible to design a two-speed motor that has two main windings and only one auxiliary winding. The latter may be made to work in conjunction with either the high-speed or low-speed main winding. Provision must be made so that the motor will start only when the line switch is closed in the position that includes a main and its auxiliary. The wiring must not permit the main that has no corresponding auxiliary to be connected to the line when it is desired to start the motor; however, after the motor comes up to speed on the main-auxiliary combination, it may be switched to the other speed.

Figure 51 illustrates the wiring connections for a six- and eight-pole motor in which the consequent-pole auxiliary is designed to operate with the conventional six-pole main winding. A special SPDT centrifugal switch (like that used in Fig. 35 for the two-value capacitor motor) must be employed in conjunction with the DPDT line switch, to prevent the operator from accidentally connecting the eight-pole consequent-pole main winding to the line when the motor is started. If the wiring is carefully studied, it will be observed that the motor will start only if the line switch is closed in the "up" position. Moreover, when the line switch is closed in the "down" position, the eight-pole consequent-pole winding is connected to the line only after the motor comes up to speed, so that the *R* contacts on the centrifugal switch are closed. The motor cannot be started on the low speed (down) side of the line switch; under this condition the open *R* contacts open-circuit the eight-pole winding.

Two-winding Two-speed Motors Using a Special Design

Special two-speed split-phase motors have been developed in which only two windings, one main and one auxiliary, are employed. Such designs always arrange and connect the coils in accordance with the fundamental winding principles already discussed but do so in rather unique ways.

Figure 52 illustrates one such design in which a single concentric-type main winding and a similar auxiliary winding are arranged in a 36-slot stator for six-pole or eight-pole operation of a capacitor-start split-phase

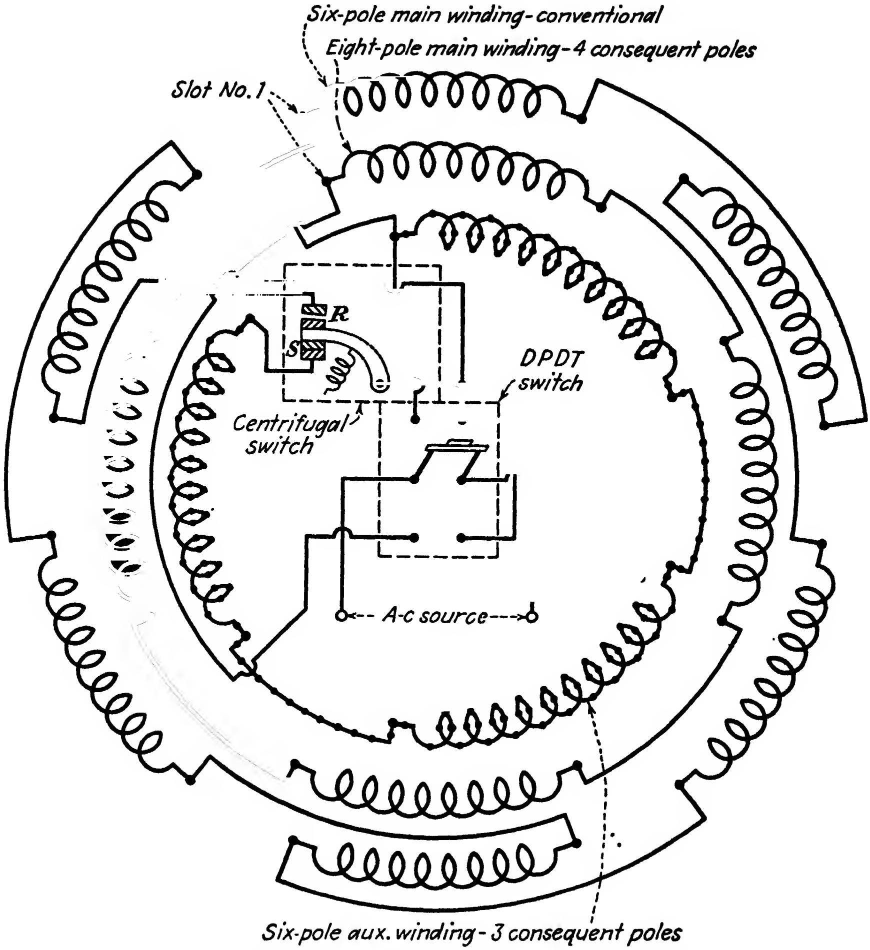


FIG. 51. Three-winding diagram for a two-speed motor. Only the outer six-pole main is a conventional winding. The second main has four pole groups and is connected as an eight-pole consequent-pole winding. The single auxiliary has three pole groups and is used only with the six-pole main winding. This motor must be started on the high-speed side first (DPDT switch up).

motor. When the TPDT line switch is closed in the "up" position, the currents flow through the coils so that the speed will be that of a six-pole motor; the *single-headed arrows* on the conductors in the slots may be traced for this connection. Note particularly the *north* and *south* pole

spans of the six- and eight-pole combinations; these are labeled N_6 and S_6 for the six-pole connection, and N_8 and S_8 for the eight-pole connection. Also important is the position and coil arrangement of the auxiliary wind-

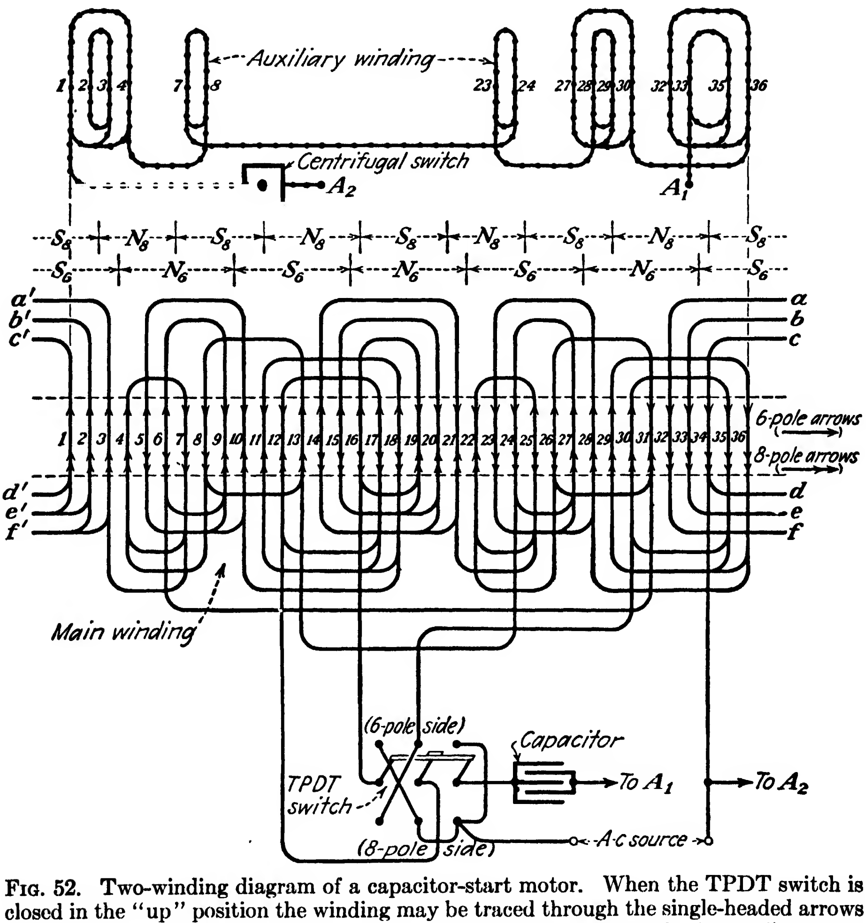


FIG. 52. Two-winding diagram of a capacitor-start motor. When the TPDT switch is closed in the "up" position the winding may be traced through the single-headed arrows in the slots for six-pole operation. When the switch is closed in the "down" position the winding may be traced through the double-headed arrows for eight-pole operation.

ing, so that it will function in conjunction with either the six- or eight-pole main winding connection.

Since a winding such as this must serve for two speed combinations, it is necessarily a compromise of two single-speed windings. And although there is much saving in winding space and winding time, the starting and running torques will be considerably less than those of conventional single-speed motors. Such windings, therefore, have limited application.

Summary

1. Many applications of single-phase motors require two-speed operation. For such service, four-winding, three-winding, and two-winding motors are available.

2. Two-speed winding motors operate at two speeds that are widely different, a decided disadvantage when stepless control is desired.

3. The speed at which a motor will rotate is inversely proportional to the number of poles for which the winding is connected.

4. Two-speed motors are physically much larger than single-speed motors of equivalent horsepower and speed ratings.

5. In four-winding two-speed motors, only one set of two windings, a main and an auxiliary, is used at a time; the second set of two windings is idle.

6. In four-winding motors, the centrifugally operated switch is made to open at the lower of the two possible speeds, the one that is somewhat below the value that is best for the higher speed winding.

7. The directions of rotation for both speeds of two-speed motors may be the same or opposite. When opposite, it is necessary that the motor come to a complete stop, when operating at one speed, *before* it is switched to the other speed.

8. In conventional windings, adjacent pole groups always carry currents in opposite directions at any instant.

9. In consequent-pole windings, all pole groups carry currents in the same direction at any instant.

10. There are always as many magnetic flux paths (and formed poles) as pole groups in conventionally connected windings.

11. There are always twice as many magnetic flux paths (and formed poles) as pole groups in consequent-pole windings.

12. Magnetic flux paths in consequent-pole windings span about one-half the circumferential distance of those spanned by conventional flux paths.

13. Consequent-pole windings are so called because the "added" poles are formed as a consequence of the fact that the pole groups are connected to carry currents in the same direction.

14. In four-winding two-speed motors, one main is usually connected in the conventional manner. The other main and the two auxiliaries are connected as consequent-pole windings.

15. In three-winding two-speed motors, one main is usually connected in the conventional manner. The other main and the auxiliary are connected as consequent-pole windings.

16. In three-winding two-speed motors, the auxiliary winding may be made to work in conjunction with either the high-speed or low-speed winding.

17. In a three-winding two-speed motor, the wiring must not permit the main that has no corresponding auxiliary to be connected to the line when the machine is started.

18. Special two-winding two-speed motors have been developed. Although the winding arrangements are somewhat complicated they follow fundamental winding principles. Such motors generally develop lower values of starting and running torque than conventional single-speed motors.

CHAPTER 7

Winding Types and Coils for Polyphase Machines

Thus far the discussions have dealt with single-phase windings. These are placed in machines, of comparatively small sizes and ratings, that are employed in applications where polyphase service is not available or where polyphase equipment would be unsuitable or too expensive. As preparation for a more detailed study of two- and three-phase windings, it will be the purpose of this chapter to consider the several types generally used in modern polyphase machines.

Phase Displacements in Two- and Three-phase Machines

When referring to windings in modern polyphase machines, it is always implied that they are either two-phase or three-phase. In a two-phase alternator, there are two independent or interconnected windings in which two emf waves are generated that are displaced *in time* by 90 electrical degrees; in a three-phase alternator, there are three interconnected windings in which three emf waves are generated that are displaced *in time* by 120 electrical degrees. Two-phase motors have two independent or interconnected windings that are displaced *in space* by 90 electrical degrees, and which take power from a two-phase electrical system; three-phase motors have three interconnected windings that are displaced *in space* by 120 electrical degrees, and which take power from a three-phase electrical system.

The generated voltages of two- and three-phase systems may be represented by the sine waves of Fig. 53. Such voltage waves may be generated in the two- or three-phase windings of alternators or "fed" to corresponding windings in two- or three-phase motors.

Referring to the two-phase sketch of Fig. 53*a*, it will be observed that phase B lags behind phase A by 90 electrical degrees, because the maximum voltage value of phase B, E_{mB}, occurs 90 electrical degrees later than the maximum voltage value of phase A, E_{mA}. In the alternator, such a *time* displacement of voltages can be produced only if two independent windings are placed in the core so that they are displaced from each other *in space* by 90 electrical degrees. Moreover, if a two-phase motor is to operate satisfactorily when connected to such a system, it too must have two

independent windings that are physically separated in the core by 90 electrical degrees.

Likewise, Fig. 53*b* shows that phase *B* lags behind phase *A* by 120 electrical degrees and that phase *C* lags behind phase *B* by 120 electrical degrees; note that E_{mB} lags behind E_{mA} by 120 degrees and that E_{mC} lags

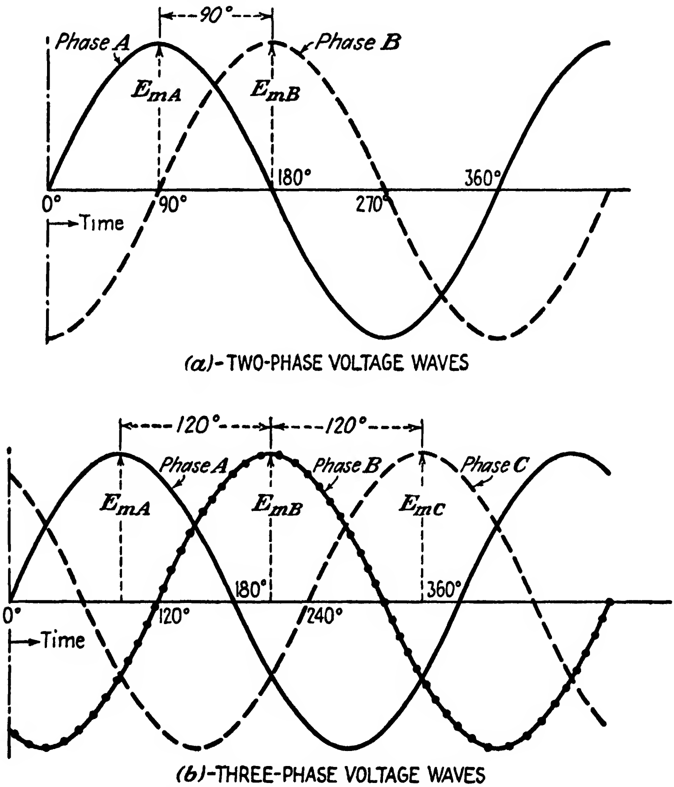


FIG. 53. Voltage waves in two-phase and three-phase systems.

behind E_{mB} by 120 degrees. Thus, in the alternator, a *time* displacement of voltages is produced only by placing three independent windings in the core so that they occupy positions, *in space*, 120 electrical degrees apart. Concerning a three-phase motor, it is also necessary that there be three independent windings in the core, physically displaced from each other by 120 electrical degrees.

Summarizing then, *a polyphase machine is one having as many independent windings as the number of phases in the system, and in which the space displacement of the windings in the core is the same as the time displacement of the corresponding voltages in the system.*

Elementary Two-phase Winding

Figure 54 illustrates how the coils of a two-phase winding are arranged and connected so that there will be a space displacement of 90 electrical degrees between phases. The sketches were drawn for an extremely elementary four-pole grouping of eight coils placed in 16 slots. Each phase, therefore, has four coils arranged as in Fig. 54*a* and connected in series as in Fig. 54*b*. Since the distance between adjacent poles is always exactly 180 electrical degrees (slots 1 to 5), the starting points of phases *A* and *B*, that is, S_A and S_B, are correct if they emerge from slots 1 and 3, 90 electrical degrees apart. Note, then, that each phase consists of a series-connected set of alternate coils and that the two phases are entirely independent of each other. Considered from the standpoint of an alternator, where a four-pole structure sweeps from left to right, phase *A* will be ahead of phase *B*, *in time*, by 90 electrical degrees. Thus, two voltage waves similar to Fig. 53*a* will be developed; the frequency will, of course, depend upon the speed of rotation of the poles.

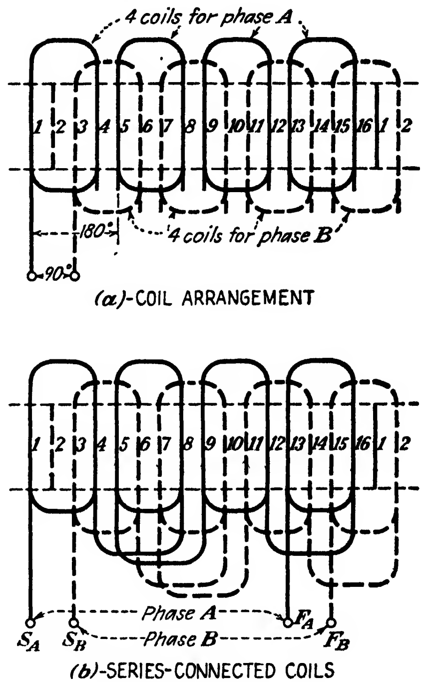


FIG. 54. Arrangement and connections of coils in an elementary 16-slot 4-pole 2-phase machine.

It should be pointed out that in actual winding practice, discussed in subsequent chapters, there is always more than one coil under each pole per phase; moreover, it is not necessary that all the pole groups be connected in series.

Elementary Three-phase Winding

An extremely elementary four-pole grouping of 12 coils in 24 slots is shown in Fig. 55 to illustrate a three-phase winding; in this diagram the three phases are displaced from each other in space by 120 electrical degrees. Since the distance between slots 1 and 7 is exactly 180 electrical degrees (one pole span), adjacent slots are 30 degrees apart (180/6 = 30). Thus, slots 1 and 5 are displaced 120 degrees, as are slots 5 and 9. It is, therefore, correct for phases *A*, *B*, and *C* to start, respectively, in slots 1, 5, and 9.

This point is of very special importance in three-phase windings, because the proper space displacement of 120 electrical degrees is achieved in this way. Note then that S_A, S_B, and S_C emerge from slots 1, 5, and 9 and that each independent phase consists of four series-connected coils. Again,

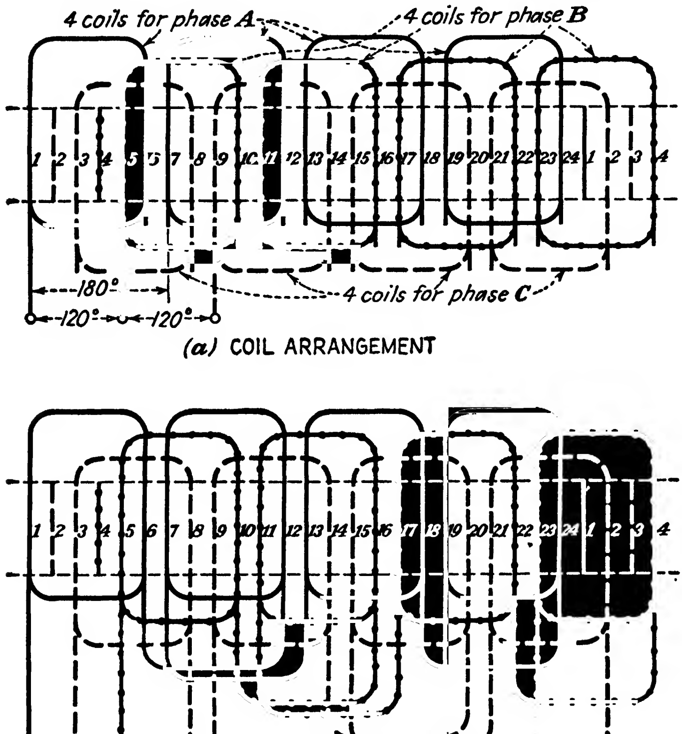


FIG. 55. Arrangement and connections of coils in an elementary 24-slot 4-pole 3-phase machine.

considered from the standpoint of an alternator, where a four-pole structure sweeps from left to right, phase B lags behind phase A by 120 degrees, and phase C lags behind phase B by 120 degrees. Hence, three voltage waves similar to Fig. 53b will be developed.

It is always well to remember that any polyphase winding diagram, two-phase or three-phase, is essentially a combination of two or three simple single-phase windings, each one of which can be independently traced from its start S to its finish F; moreover, in such tracing, all phases will be found to have the same total number of coils.

Types of Polyphase Winding

There are three general types of polyphase winding, namely, (1) the concentric-chain, (2) the wave, and (3) the lap. Each type has its fields of application that have been found, by experience, to suit certain details of machine construction and operation. For example, concentric-coil windings are frequently used in slow-speed, large diameter alternators; wave windings are ideal for the rotors of wound-rotor induction-type motors; while lap windings are generally employed in the stators of most a-c motors and high-speed alternators. These classifications are, of course, only general but, in the main, have few exceptions.

Concentric-chain windings are *single-layer* in construction; *i.e.*, each slot contains one coil-side. Lap and wave windings are nearly always double-layer, so that each slot will contain two coil-sides, one on top of the other; one coil-side will be part of a coil on the left, while the other coil-side will be part of another coil on the right.

Coil Constructions

Several styles of coil construction are used in polyphase machines. The one that has wide application for the stators of motors up to about 100 hp and 500 volts is the so-called *fed-in* coil. It is usually diamond-shaped and contains many turns of rather small wire. The winding procedure, then, requires that the operator feed the individual wires of each coil-side into slots, through the narrow opening formed by overhanging teeth. Top and bottom coil-sides in the slots are separated from each other by good insulating paper. The coil ends must, however, be individually taped while the winding progresses, because the wires have to be spread apart before they can be fed into the slots. When properly and carefully installed, such a winding provides excellent mechanical and electrical strength.

When the slots are open, as they are in machines of the larger sizes, the winding consists of coils that are completely formed, taped, dipped, and baked. The wires for the diamond-shaped coils are often rectangular in section and are carefully laid side by side and on top of one another. This construction conserves valuable slot space so that a maximum of copper area may be used. These windings also have two coil-sides per slot, one on top of the other, with the individual coils formed to exact dimensions as they finally appear in the machine.

Hand-wound or *threaded* coils, though not used much in this country, involve a considerable amount of hand labor. Each coil is formed in place by the winder as he passes a single wire through a slot, bends it in shape around a wooden form, threads it back through a second slot the proper distance away, and repeats the process until the desired number of turns have been made. Such windings are single-layer.

Pushed-through coils, for rather large machines, consist of a number of U-shaped wires that are pushed through a pair of properly separated slots until the bend approaches the core. The open ends on the opposite side are then bent around and connected together to form a continuous coil of wire; the joined ends are, of course, soldered and taped. This construction also involves a considerable amount of hand work and is, for this reason, not particularly popular in this country.

Straight bars and involute connectors were used at one time in large ma-

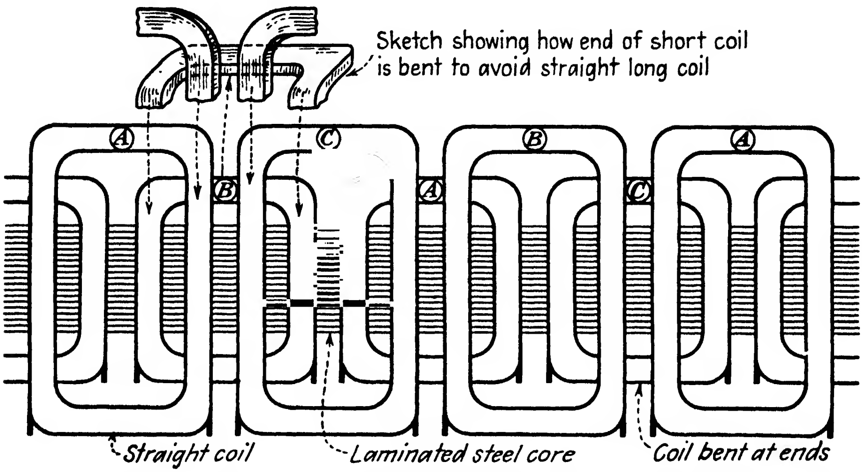


FIG. 56. Arrangement of coils in a three-phase single concentric-chain winding. Note the two different coil sizes and the designations A, B, and C for the three phases.

chines where each coil consisted of heavy single conductors. In this winding the individual rectangular-shaped copper bars were pushed through the slots, after which proper pairs were joined together by involute connectors. This construction has been largely abandoned, because it is now recognized that a bundle of small conductors connected in parallel develop less copper loss heating than a single conductor of the same total cross-sectional area.

Concentric-chain Windings

In principle, the concentric-chain type of winding is quite similar to the single-phase coil arrangement previously discussed in Chap. 3. There are, however, several constructional differences between the two types, because the polyphase winding must provide for two or three phases that are displaced from each other in space by the proper number of electrical degrees. On the other hand, each of the phases of a polyphase winding may be considered as equivalent to an independent single-phase.

Figure 56 illustrates a *single concentric-chain* winding for a three-phase machine; the word *single* implies *that each phase has but one coil per pole.* Since this type of winding must have a core with three slots per pole, a 12-pole motor, for example, would have a 36-slot stator and a total of 18 coils; there would be, therefore, six coils in each phase.

An important distinguishing feature of *this type of winding* is that it *has coils of different shapes.* Clearly shown in Fig. 56 are the long, straight coils and those that are shorter but bent backwards at the ends to avoid the straight, long coils. The reason for the bend is that the coils of the

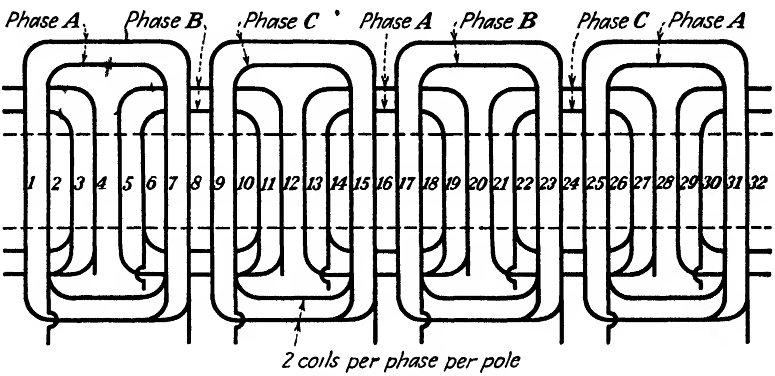


FIG. 57. Arrangement of coils in a three-phase double concentric-chain winding with four different coil sizes. The long coils are straight and the short coils are bent at the ends to avoid the straight coils.

various phases must cross around each other in passing from one slot to another on the same circumference level; these windings are single-layer. The span of all coils is, however, the same. It should also be noted that the term *chain* has reference to the resemblance to the links of a chain after the winding is in place.

Figure 57 is a simplified single-line diagram illustrating a *double concentric-chain* winding for a three-phase machine; the word *double* implies that *each phase has two coils per pole.* Also note that the two coils per phase per pole are concentric with respect to each other; this indicates the reason for the other term in the name *concentric-chain* winding. A winding such as this would require six slots per pole (twice as many as in the single concentric-chain winding); a 24-pole machine, for example, would have 144 slots and 72 coils, with 24 coils in each phase. Four different sizes of coils would be needed to construct a double concentric-chain winding.

Triple concentric-chain windings have three coils per phase per pole that are concentric with respect to each other and six different coil sizes. For three-phase the number of slots per pole would be nine; an eight-pole

machine, for example, would require a 72-slot core and a total of 36 coils, with 12 coils per phase.

A triple concentric-chain winding for a two-phase machine is illustrated by Fig. 58. It will be observed that it has six different coil sizes, the long ones representing phase A, and the short, bent coils belonging to phase B. A triple two-phase concentric-chain winding requires six slots per pole; a 10-pole machine, for example, would have 60 slots and 30 coils with 15 coils per phase.

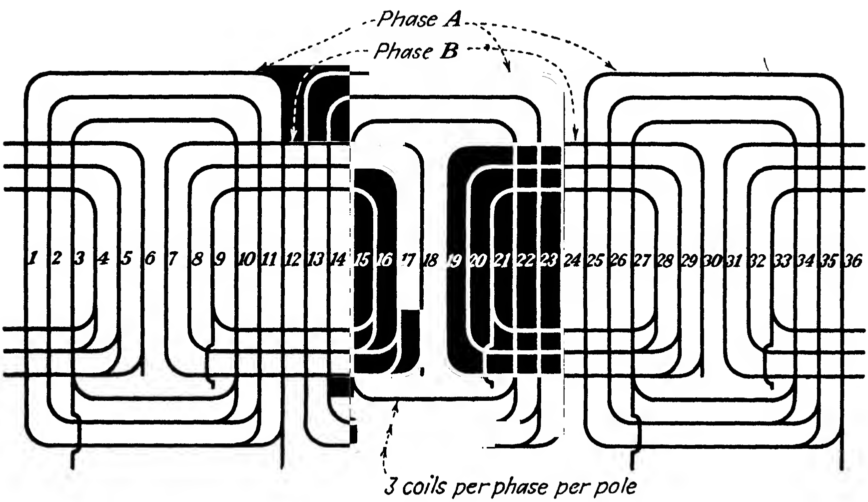


FIG. 58. Arrangement of coils in a two-phase triple concentric-chain winding with six different coil sizes. Note that all the long coils belong to phase A while the short, bent coils constitute phase B.

An important difference between two- and three-phase concentric-chain windings should be noted. Referring to Figs. 56 and 57, it will be seen that all three phases have exactly the same number of long and short coils for every four poles. This uniform distribution of long and short coils is not possible with two-phase windings, where each phase has either one or the other coil sizes and shapes. However, in constructing the coils for a two- or three-phase machine, it is customary to use the same *length of wire* in the long and short ones; the bends at both ends compensate for the shorter axial length in the short coils.

Wave Windings

The coils used to construct a wave winding in an a-c machine are identical with those employed in a d-c armature winding. The wire ends of the latter coils are connected to commutator segments, while those in polyphase a-c

windings are joined together to form properly arranged phases. Figure 59 illustrates a typical wave coil of several turns of wire for use in a core with open slots. It will be observed that the front and rear "knuckle" bends place the left coil-side above the level of the right coil-side. This construction is necessary for a double-layer winding in which all coils have the same size and shape. Another point to be noted is the way in which the coil ends are bent outward from the coil-sides so that they may be conveniently connected to other coil ends similarly bent. And, as in d-c windings, when successively joined coils are traced through an entire phase, the winding

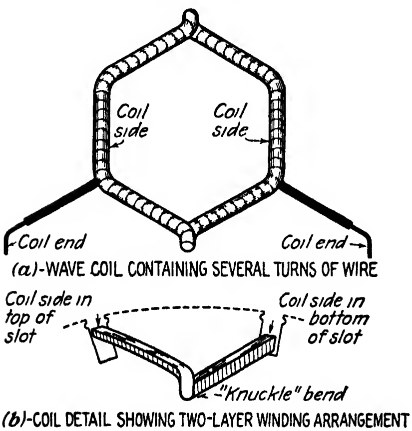


FIG. 59. Sketches illustrating wave-winding coil construction.

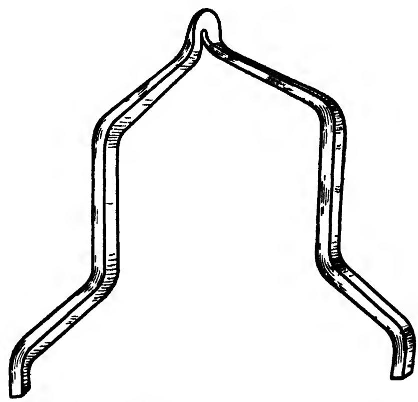


FIG. 60. Single-turn wave coil of heavy copper strap.

appears to follow a series of waves; it is for this reason that the term *wave winding* has been applied to this construction.

In large machines it is sometimes desirable to use single-turn coils of heavy copper strap. These are formed as represented by Fig. 60, when the core has open slots. With partially closed slots the coils are shaped with straight sides; the open ends are pushed through axially from one end of the core, after which they are bent outward in the usual way to be connected to other similarly formed coils.

Figure 61 represents a 36-slot core in which all the coils of one phase are shown properly located. To avoid confusion and to simplify the drawing of complete and apparently complex winding diagrams, single-turn coils are indicated and no connections between coils are included. (The latter will be treated in detail subsequently, for which reason the individual coils and their ends have been labeled for later reference.) Note particularly that (1) all coils have exactly the same size and shape, in contrast to those used in concentric-chain windings; (2) there are two coil-sides per slot, with the continuous line (left side of the coil) representing the top coil-side,

and the dash line (right side of the coil) representing the bottom coil-side; and (3) the coil ends are bent outward from the sides so that the proper coils may be joined together conveniently without the necessity of using jumpers.

A significant advantage of wave windings is that cross connections between groups of coils are reduced to a minimum. This feature is especially

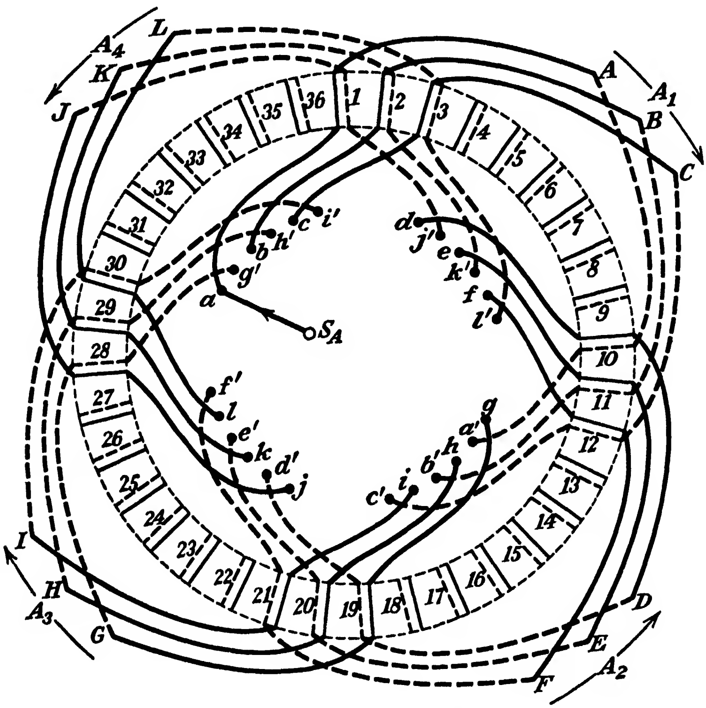


FIG. 61. Single-turn wave coils arranged in 12 slots of a 36-slot core for one of the phases of a 3-phase winding.

important in the construction of rotor windings, because of the limited available space and the fact that a simple, compact arrangement helps to keep a revolving structure mechanically balanced.

Double-layer wave windings always have as many coils as slots. (Compare this with single-layer concentric-chain windings which have half as many coils as slots.) This means that a 36-slot machine, for example, will have a total of 36 coils; if the winding is three-phase, there will be 12 coils per phase, as shown in Fig. 61. (To clarify the latter diagram the coils for the other two phases have been omitted, but they would, of course, occupy the vacant slots represented by the short continuous and dash lines.)

Lap Windings

The lap winding is the type most commonly employed on the stators of polyphase a-c machines. In appearance and construction the coils are identical with those used in d-c armatures. And, except for the fact that the coil ends are brought out near one of the "knuckle" bends, they are similar to wave coils. Figure 62 illustrates a formed lap coil having several turns of wire, for use in an open-slotted core. Since lap windings are also double-layer, the "knuckle" bends place one coil-side, the left side in this case, above the level of the right side.

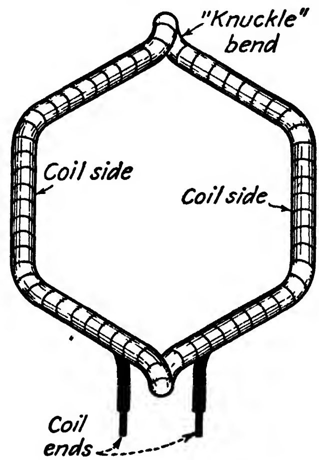


FIG. 62. Lap coil containing several turns of wire for an a-c winding.

When the core has overhanging teeth, *i.e.*, partially closed slots, the coils are not taped when they are first made. Instead, the wire is wound on a form in the shape of a diamond, after which the individual wires of each coil are fed into the slots, one or two at a time, through the narrow openings between teeth. The coils are taped after they have been put in place and are later hammered into their final form with a rawhide mallet and appropriate fibre or wood blocks.

Using a diagram similar to that of Fig. 61, one phase of a three-phase lap winding, properly arranged in the 36-slot stator, is represented by Fig. 63. Again, for convenience in studying this type of winding, no connections have been made between coils. The latter have, however, been drawn to indicate that there are several turns per coil, instead of the single-turn coils of the wave-winding diagram; note the two ends emerging from the inside loop of each coil.

The other two phases would, of course, occupy the remaining 24 slots

of the figure represented by the short continuous and dash lines, and would be connected in such a way that a 120-electrical-degree displacement would exist between the three phases.

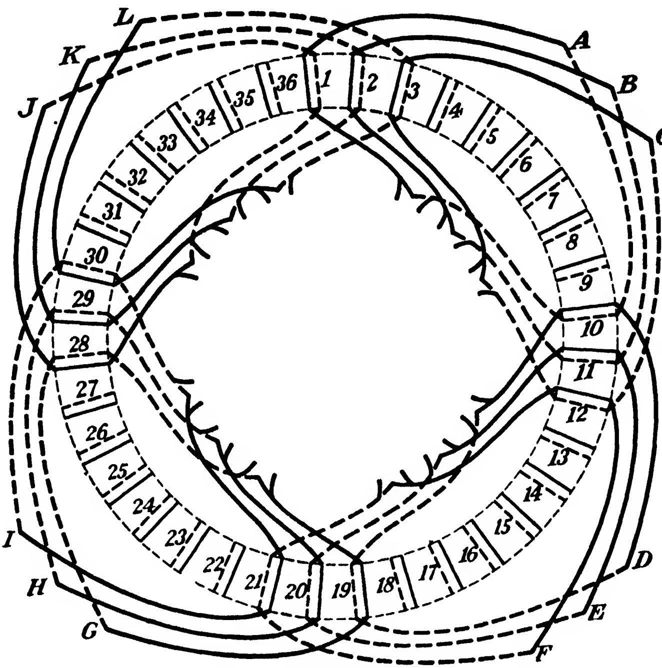


FIG. 63. Lap coils arranged in 12 slots of a 36-slot core for one of the phases of a 3-phase winding. Each coil is similar to that illustrated by Fig. 62.

Summary

1. Windings used in polyphase motors and alternators are generally designed for two- or three-phase service.

2. In two-phase machines there are two single-phase windings that may or may not be interconnected; they are displaced with respect to each other in space by 90 electrical degrees.

3. In three-phase machines there are three single-phase windings that are generally interconnected; they are displaced with respect to each other in space by 120 electrical degrees.

4. A polyphase machine is one having as many independent windings as the number of phases of the system, and in which the space displacement of the windings in the core is the same as the time displacement of the voltages in the system.

5. Any polyphase winding diagram, two-phase or three-phase, is essen-

tially a combination of two or three simple single-phase windings, each one of which can be independently traced from its start to its finish. In any such winding all phases are wound identically.

6. There are three general types of polyphase winding, namely, (*a*) the concentric-chain, (*b*) the wave, and (*c*) the lap.

7. Concentric-chain windings are single-layer; wave and lap windings are double-layer.

8. There are several styles of coil construction used in polyphase windings, namely, (*a*) fed-in coils, (*b*) hand-wound or threaded coils, (*c*) pushed-through coils, and (*d*) straight bars and involute connectors.

9. When the core of a machine has open slots, the coils can be completely formed, insulated, and baked before they are used. With partially closed slots, the individual wires of the formed coils must be threaded through the narrow openings between slots, one or two at a time; the taping and insulating must be done after the winding is in place.

10. Hand-wound or pushed-through windings involve a considerable amount of hand labor; such windings have been largely abandoned in this country.

11. Concentric-chain windings are similar in principle to the coil arrangement employed in concentric windings for single-phase machines.

12. Single, double, triple, or multiple concentric-chain windings refer to the fact that there are one, two, three, or more concentric coils per phase per pole.

13. All concentric-chain windings have coils of different sizes and shapes. In single, double, triple, etc., concentric-coil windings there are two, four, six, etc., different sizes and shapes.

14. The coils in any double-layer lap or wave winding are exactly identical.

15. In three-phase concentric-chain windings, all three phases have exactly the same number of differently shaped coils for every four poles.

16. In two-phase concentric-chain windings, each phase has a set of differently shaped coils. The coils are constructed, however, so that all have the same length of wire.

17. The coils of a-c wave windings are similar in construction to those used in d-c machines.

18. Wave windings are so named because the coils may be traced through a series of waves from one end of a phase to the other.

19. Completed wave windings have few cross-connectors. This feature makes this type of construction ideal for rotors in a-c machines, where there is a limited amount of space and because the revolving structure can be balanced more easily.

20. Double-layer wave windings always have as many coils as slots.

21. Lap windings are most commonly employed in the stators of a-c machines.

22. The lap-coil construction is similar to that of the wave coil, except for the way in which the ends are brought out; in the wave coil the ends are brought out from the coil-sides and are bent outward, while in the lap winding the ends are brought out near one of the "knuckle" bends.

23. In most of the smaller machines the slots are partially closed. This requires coils that are form-wound but untaped, after which the individual wires are fed into the slots, one or two at a time. The completed winding is then hammered in place by a rawhide mallet and fibre or wood blocks.

CHAPTER 8

Concentric-chain Windings

The general aspects of coil construction and winding arrangements were discussed in Chap. 7. In further considering concentric-chain windings it is important to remember, among other things, that (1) several shapes and sizes of coil are necessary and (2) the total number of coils is one-half the number of slots in the core. Remembering these points, as well as the polyphase-winding principles previously discussed, it will be the purpose of this chapter to consider how concentric-chain windings are laid out and connected for polyphase service.

Half-coiled Windings

The fact that the total number of coils in a concentric-chain winding is one-half the total number of slots in the core implies that each phase will have one-half as many coils as the number of slots allotted to it (the number of slots per phase = total slots/phases). Thus, each phase of a two-phase winding will require one-fourth as many coils as the number of slots, while the number of coils in each phase of a three-phase winding will have to be one-sixth the total number of slots. Under this condition there will always be one-half as many pole groups per phase as the number of poles for which

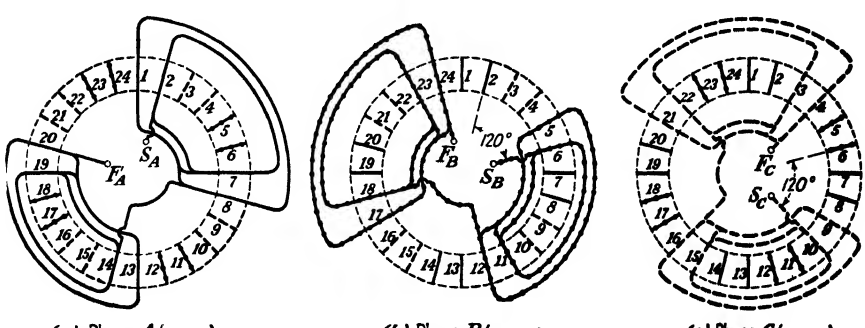


FIG. 64. Arrangement and connections of the coils in a three-phase double concentric-chain winding. The individual phases are shown separated with the proper space displacements indicated. Refer to Fig. 65 for the composite winding diagram for this 24-slot 4-pole machine.

the machine is wound. In other words, considered from the point of view of single-phase winding theory (Chap. 6), a concentric-chain winding is a consequent-pole winding.

Figure 64 illustrates why a single-layer concentric-chain winding is a consequent-pole winding. The diagram for a 24-slot four-pole machine is shown divided into three parts, so that the coils for the individual phases may be clearly seen in their properly allotted portions of the core. Note that each phase has two pole groups of two coils each. Since they are connected in the same direction, four magnetic poles will be created. Polyphase windings of this type, in which there are half as many pole groups as poles, are more often referred to as *half-coiled* windings. This term has been found to be more applicable than the consequent-pole designation because it better distinguishes this winding from the so-called *whole-coiled* winding, discussed in a subsequent chapter.

Laying Out a Three-phase Concentric-chain Winding

In laying out a concentric-chain winding for any polyphase machine, it is first necessary to allocate definite sets of slots to each phase under each pole. This is readily done (1) by dividing the total number of slots into pole sections (total slots/poles) and then (2) subdividing each set of slots per pole into as many parts as phases. Referring again to Fig. 64, it is seen how this is done for a 24-slot 4-pole 3-phase winding. Since there are six slots per pole (24 slots/4 poles) there will be two slots per pole per phase ($6/3 = 2$). The first two slots under each pole are then arbitrarily assigned to phase A; these are slots 1, 2, 7, 8, 13, 14, 19, and 20. Phase B must be 120 electrical degrees distant from phase A, so that slots 5, 6, 11, 12, 17, 18, 23, and 24 must be assigned to it. The remaining slots will then belong to phase C; these are 9, 10, 15, 16, 21, 22, 3, and 4. Using the phase A slots, the two sets of concentric coils are next drawn in and connected in series as in Fig. 64*a*; note that the start of this phase, S_A, emerges from slot 2. Since slot 6 is 120 electrical degrees from slot 2 (there are 30 degrees between slots), the start of phase B, S_B must be there; *this is extremely important.* An error that is sometimes made is to start phase B from slot 4; this is incorrect because slot 4 is only 60 electrical degrees from slot 2. Phase B is next drawn in and connected in series, as in Fig. 64*b*. With the start of phase C, S_C emerging from slot 10, 120 electrical degrees from slot 6, the last two pole groups are finally drawn in and connected in series, as in Fig. 64*c*.

A complete winding diagram, illustrating how all three phases appear in the core, is given in Fig. 65. In practice, it is customary to interconnect the three phases to form a *star* (Y) or a *delta* (Δ). For the star connection, it is merely necessary to join together three similar terminals, that is,

F_A, F_B, and F_C, call it the *star* point, and use the other three points, S_A, S_B, and S_C, as line terminals; this has been done in Fig. 65. This typical diagram indicates clearly how all three phases are identical, there being four different shapes and sizes of coils in each one. This latter point is always true for every four poles of a multiple three-phase winding.

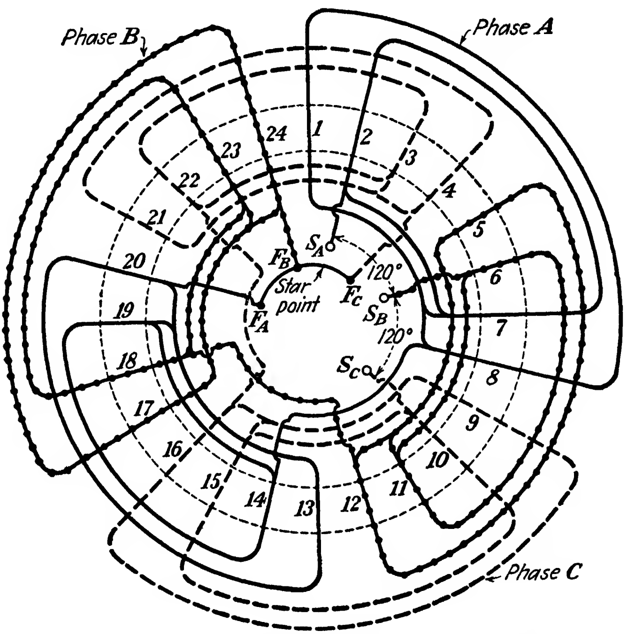


FIG. 65. Complete 3-phase 4-pole double concentric-chain winding for a 24-slot machine. The three phases are connected in *star* (Y) by joining together F_A, F_B, and F_C; S_A, S_B, and S_C are line terminals. (Compare with Fig. 64.)

Simplified Diagram for Concentric-chain Windings

It is obvious that a complete winding diagram, such as Fig. 65, is generally too complex for analysis; this is especially true when there are many more slots and poles and when certain parallel coil-group combinations are used. A greatly simplified type of diagram may, however, be employed for such a winding, and can serve just as effectively only if its meaning is clearly interpreted to represent the complete winding. This has been done for the foregoing 24-slot 4-pole 3-phase winding in Fig. 66.

Note that (1) each pole group of two coils has been carefully located, (2) the pole groups are properly connected in series in the same direction, (3) a 120-electrical-degree displacement is maintained between phases, and (4) interconnection of the three phases into a star has been made by joining F_A, F_B, and F_C.

This type of diagram will be used frequently to represent many of the windings that follow.

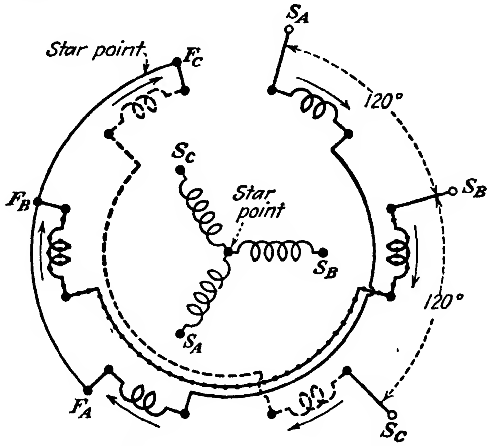


FIG. 66. Schematic diagram of the double concentric-chain winding shown in Fig. 65.

Laying Out a Two-phase Concentric-chain Winding

Following the procedure outlined for laying out a three-phase concentric-chain winding, Figs. 67, 68, and 69 have been drawn to represent a similar type of winding for two-phase service. Since the 24-slot core is used again, there will be three coils per phase per pole (12 coils/2 groups × 2 phases). Figure 67 illustrates the coil arrangements for phase A and phase B, divided

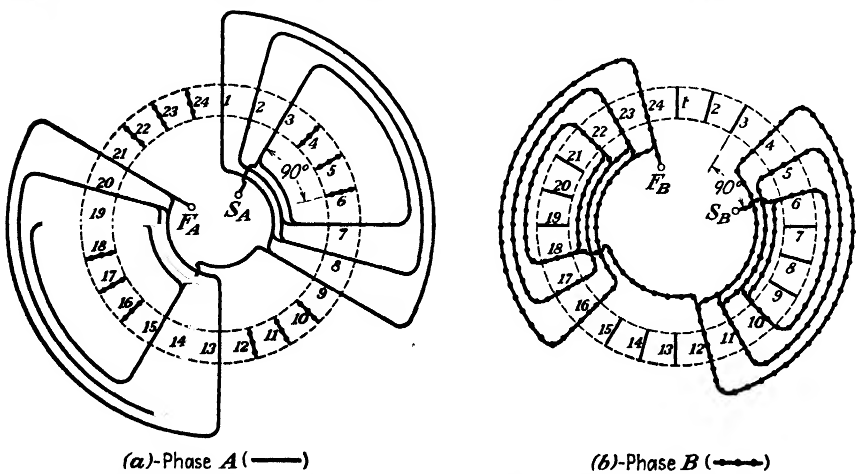


FIG. 67. Arrangement and connections of coils in a two-phase triple concentric-chain winding. The individual phases are shown separated with the proper space displacement indicated. Refer to Fig. 68 for composite winding diagram for this 24-slot 4-pole machine.

into two parts for simplicity. Note that the two phases are separated from each other by exactly 90 electrical degrees, since the distance between

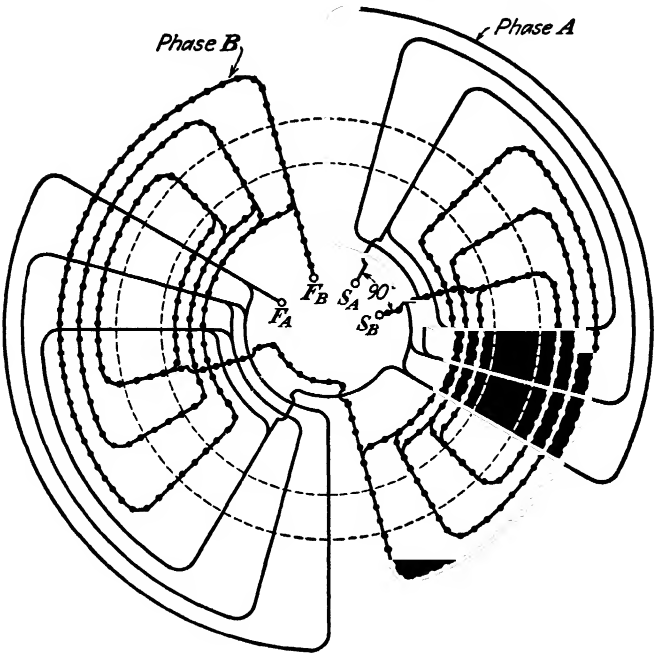


FIG. 68. Complete 2-phase 4-pole triple concentric-chain winding for a 24-slot machine. For 2-phase 3-wire service, F_A and S_B may be joined together and their junction used with S_A and F_B as line terminals.

adjacent slots is 30 degrees and the starting points of the two windings, S_A and S_B, are slots 3 and 6.

Figure 68 shows how the two phases are arranged and connected in the actual core. It will be observed that phase A has the longer coils, while phase B is made up of a set of shorter coils. As was previously pointed out, however, the total wire length of phase A would normally be the same as that of phase B.

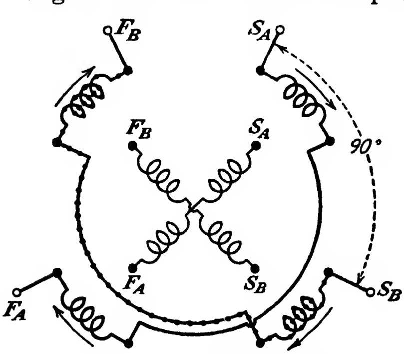


FIG. 69. Schematic diagram of the triple concentric-chain winding shown in Fig. 68.

A simplified schematic diagram of this half-coiled winding is given in Fig. 69. It is suggested that all three figures be studied together because they help to clarify important fundamental winding principles.

Typical Concentric-chain Winding Problems

Several typical examples will now be given to illustrate concentric-chain windings. These should be studied carefully in connection with the explanatory notes and their accompanying simplified diagrams.

EXAMPLE 1. Make calculations and draw a simplified diagram for a concentric-chain winding, given the following particulars: number of slots = 108; number of poles = 12; number of phases = 3; connection = star.

Solution

(*a*) Since the core has 108 slots and the winding is half-coiled, there will be a total of 54 coils (108 slots/2)

(*b*) Each phase will, therefore, have 18 coils (54 coils/3 phases)

(*c*) There being six groups of coils per phase, each pole group will contain 3 coils (18 coils per phase/6 coil groups)

(*d*) This winding will have six different sizes and shapes of coils

(*e*) After the winding is completed, the star connection is made by joining together F_A, F_B, and F_C as the star point, and using S_A, S_B, and S_C as line terminals

(*f*) Figure 70 is a simplified diagram for the example.

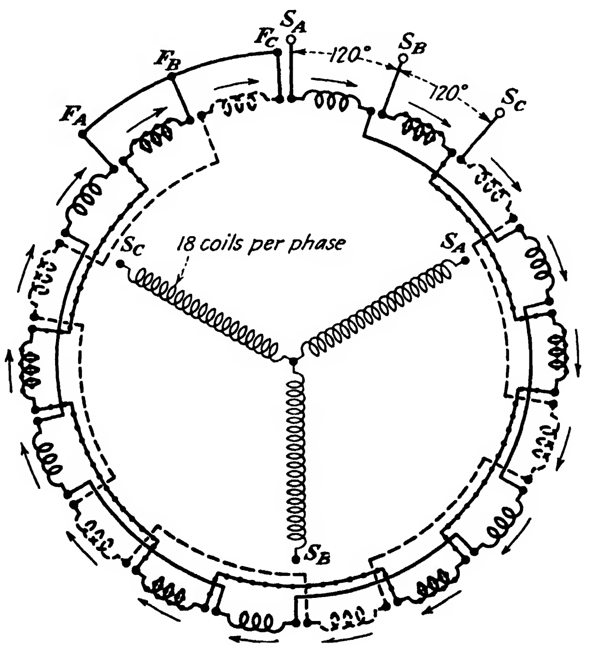


FIG. 70. Schematic diagram of a triple concentric-chain (half-coiled) winding for a 108-slot 12-pole 3-phase machine. The star connection is used (see Example 1).

EXAMPLE 2. Make calculations and draw a simplified diagram for a concentric-chain winding, given the following particulars: number of slots = 96; number of poles = 8; number of phases = 3; connection = delta.

Solution

(*a*) Total number of coils = 96 slots/2 = 48
(*b*) Coils per phase = 48 coils/3 phases = 16
(*c*) Coils per pole group = 16 coils per phase/4 coil groups = 4
(*d*) There will be eight different sizes and shapes of coils
(*e*) The delta connection is made by joining F_A to S_B, F_B to S_C, and F_C to S_A. The junctions are then used as line terminals
(*f*) Figure 71 is a simplified diagram for the example.

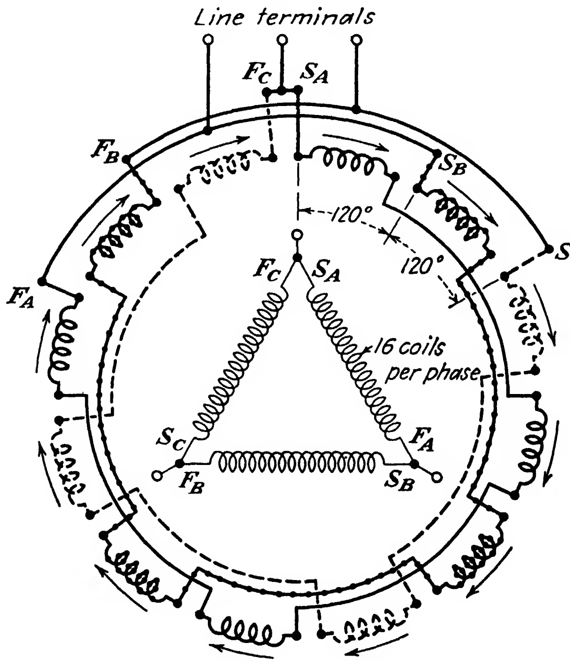


FIG. 71. Schematic diagram of a quadruple concentric-chain (half-coiled) winding for a 96-slot 8-pole 3-phase machine. The delta connection is used (see Example 2).

EXAMPLE 3. Make calculations and draw a simplified diagram for a concentric-chain winding, given the following particulars: number of slots = 96; number of poles = 16; number of phases = 3; connection = star.

Solution

(*a*) Total number of coils = 96/2 = 48
(*b*) Coils per phase = 48/3 = 16

(c) Coils per pole group = 16/8 = 2

(d) There will be four different sizes and shapes of coils

(e) Join F_A, F_B, and F_C for the star point, and use S_A, S_B, and S_C as line terminals

(f) Figure 72 is a simplified diagram for the example.

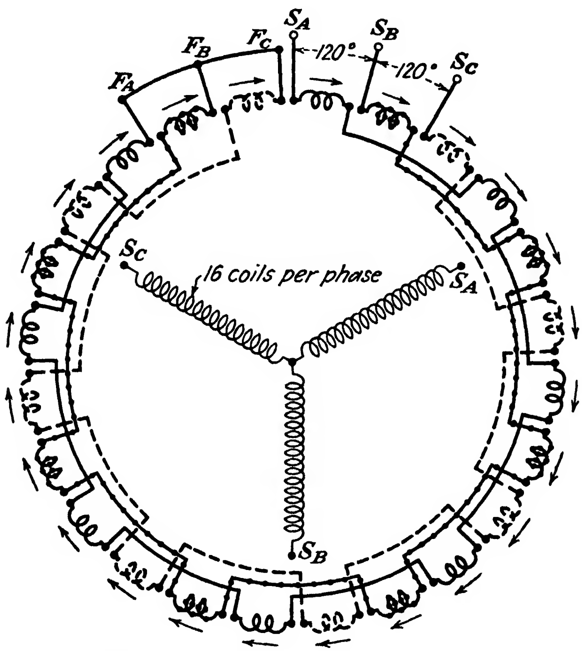


FIG. 72. Schematic diagram of a triple concentric-chain (half-coiled) winding for a 96-slot 16-pole 3-phase machine. The star connection is used (see Example 3).

EXAMPLE 4. Make calculations and draw a simplified diagram for a concentric-chain winding, given the following particulars: number of slots = 48; number of poles = 12; number of phases = 2; connection = 4-wire.

Solution

(a) Total number of coils = 48/2 = 24

(b) Coils per phase = 24/2 = 12

(c) Coils per pole group = 12/6 = 2

(d) There will be four different sizes and shapes of coils

(e) No interconnection of phases is made for the 4-wire system. Use S_A, F_A for one phase, and S_B, F_B for the second phase

(*f*) Figure 73 is a simplified diagram for the example.

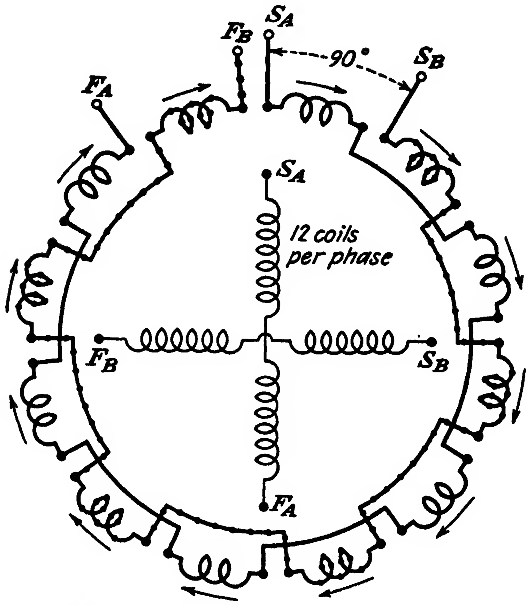


FIG. 73. Schematic diagram of a double concentric-chain (half-coiled) winding for a 48-slot 12-pole 2-phase machine (see Example 4).

Table 1 summarizes the solutions to the foregoing problems and adds three others for which the student is urged to make simplified winding diagrams.

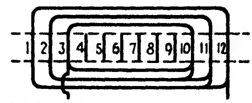
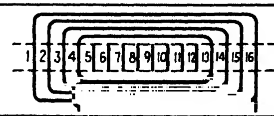
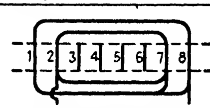
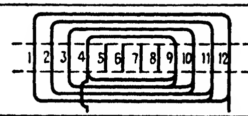
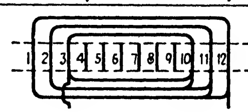
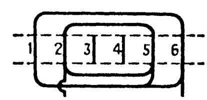
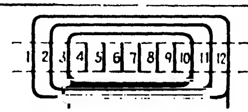
Special Coil Shapes for Concentric-chain Windings

It was previously pointed out that each phase of a three-phase winding has exactly the same number of differently shaped coils for every four poles. This means that the several coil shapes and sizes divide themselves uniformly among the three phases for every four poles. Thus, 4-, 8-, 12-, 16-, 20-, 24-, 28-, 32-, etc., pole windings are symmetrical in this respect. Furthermore, for these pole combinations there will always be two coil shapes and sizes for every *coil per pole group;* or, what amounts to the same thing, for every *three slots per pole* there will be two coil shapes and sizes. Table 1 illustrates this clearly. In Example 1, for instance, there are nine slots per pole, three 3-slot sets and, therefore, six coil shapes and sizes. Again, in Example 2, there are 12 slots per pole, four 3-slot sets and, therefore, eight coil shapes and sizes.

When the number of poles in a three-phase machine is *not* a multiple of four, the last set of coils put into the winding must be specially shaped so

that they are a sort of combination of short bent-back portions and long straight portions. To understand why this is so, it must be remembered that in single-layer windings the individual coils must be formed at the

TABLE 1. PROBLEMS AND SOLUTIONS FOR CONCENTRIC-CHAIN WINDINGS

	Given data				Solution					
Problem No.	Slots	Poles	Phases	Connection	Total No. of coils	Coils per phase	Pole groups per phase	Coils per pole group	No. of coil shapes and sizes	Sketch of one pole-group of coils
1	108	12	3	Y	54	18	6	3	6	
2	96	8	3	Δ	48	16	4	4	8	
3	96	16	3	Y	48	16	8	2	4	
4	48	12	2	4-wire	24	12	6	2	4	
5	180	20	3	Δ	90	30	10	3	6	
6	96	24	2	3-wire	48	24	12	2	4	
7	216	24	3	Y	108	36	12	3	6	

ends to cross around one another as they pass from one slot to another on the same circumference level. In the particular case under discussion, one-half of the coil span must be long axially and straight at the ends, while the other half of the coil span must be short axially and bent back at the ends. Figure 74, which shows the coils in a 36-slot core of a 6-pole machine, should make this clear. Beginning in slots 1 and 2, the long-straight coils

and the short-bent coils are installed in succession in the usual way until it is necessary to put in the last two coils from slots 33 and 34 to slots 3 and 4. A careful study of the diagram indicates that the left sides of these coils must be straight and long, while the right sides must be short and bent back. Only in this way is it possible for the specially shaped coils to cross around the others at *a*, *b*, *c*, and *d*.

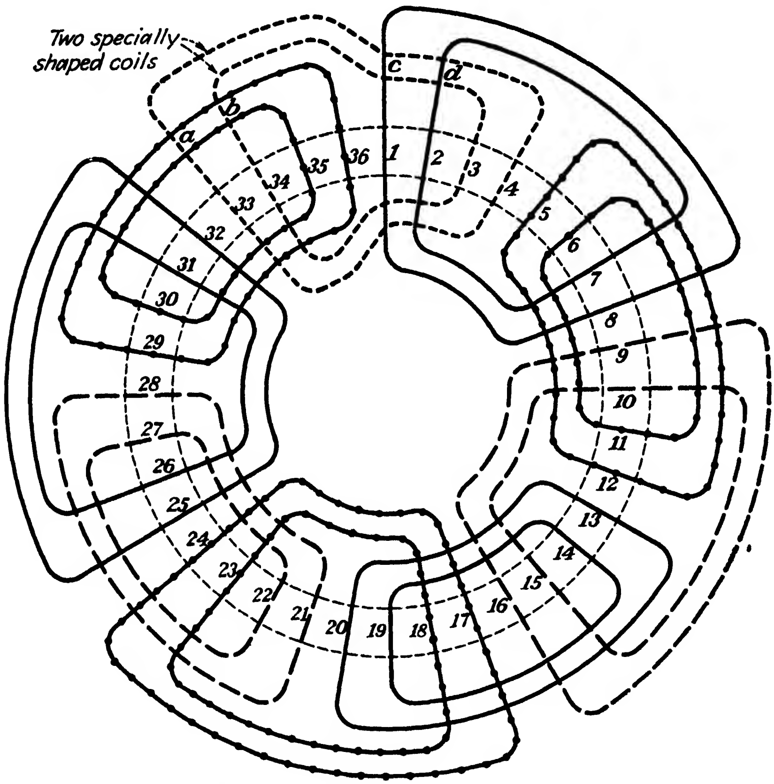


FIG. 74. Sketch showing why two specially shaped coils are required for a winding whose number of poles is not a multiple of *four*. This is a double concentric-chain winding for a 36-slot 6-pole 3-phase machine.

Summary

1. Concentric-chain windings are single-layer and, therefore, have coils of several shapes. The number of coil sizes will depend upon whether the winding is single, double, triple, etc.

2. The total number of coils in a single-layer winding is one-half the number of slots in the core.

3. Each phase of a concentric-chain winding has half as many pole groups as poles.

4. Concentric-chain windings are consequent-pole windings.

5. More frequently polyphase consequent-pole windings are called *half-coiled* windings.

6. In polyphase windings it is very important that the individual phases be properly located in the slots; they must be displaced from each other by the correct number of electrical degrees. In two-phase windings the displacement should be 90 electrical degrees; in three-phase windings the displacement should be 120 electrical degrees.

7. A three-phase star connection is made by joining F_A, F_B, and F_C for the star point, and using S_A, S_B, and S_C as line terminals.

8. A three-phase delta connection is made by joining F_A to S_B, F_B to S_C, and F_C to S_A. The junction points are then used as line terminals.

9. Each phase of a three-phase winding has exactly the same number of differently shaped coils for every four poles.

10. When the number of poles in a three-phase concentric-chain winding is not a multiple of four, the last set of coils that is installed must be specially shaped. The special shapes are a sort of combination of short bent-back portions and long straight portions.

CHAPTER 9

Wave Windings

The second of the three practical types of polyphase winding, *the wave winding,* will be considered in some detail in this chapter. It will be recalled from its general treatment in Chap. 7 that, unlike the concentric-chain winding, (1) it is double-layer, (2) all its coils are exactly identical, and (3) there is a minimum of cross connections between groups of coils. Although used in some stators, wave windings are found mainly on the rotors of induction-type machines where space limitations and the mechanical balance of a revolving structure have special importance.

Double-layer Windings

Whenever the coils of a winding are constructed so that one coil-side is placed in the top of a slot and the other coil-side occupies the bottom of another slot, all the coils can have exactly the same shape and size. Figure 59 illustrates how the "knuckle" bends at both ends of the coil make it possible to locate the coil-sides in this manner. With this arrangement, therefore, each slot contains (1) a bottom coil-side, the other side of whose coil occupies the top of another slot, and (2) a top coil-side, the other side of whose coil is in the bottom of another slot. *All coils* obviously *have the same span,* which is generally equal to 180 electrical degrees in wave windings, and this means that only *one shape and size is necessary.* Moreover, since every coil has two coil-sides, and every slot contains two coil-sides, *the total number of coils in a double-layer wave winding is equal to the number of slots.*

Whole-coiled Windings

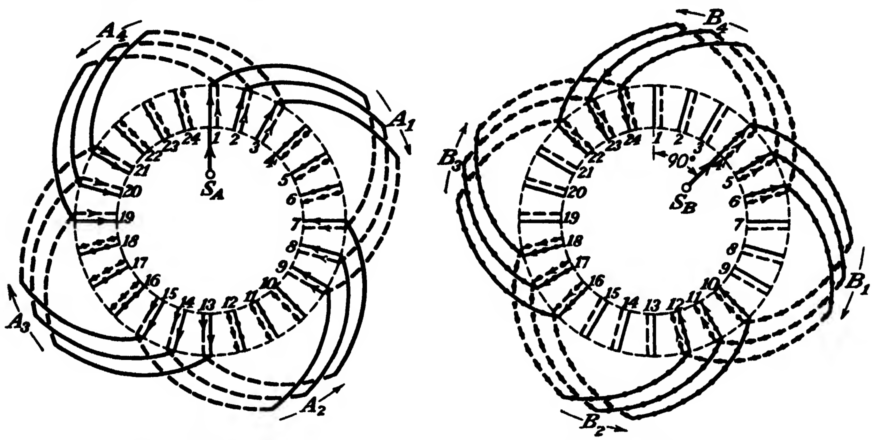
It will be recalled that the number of pole groups per phase in a single-layer winding is one-half the number of poles, because there are half as many coils as slots. A double-layer winding has, by comparison, the same number of coils as slots; this is twice as many as in an equivalent single-layer winding. Now then, since the number of coils per pole group is independent of whether the winding is single- or double-layer, it follows that *a double-layer winding has as many pole groups per phase as poles.*

Windings of this type — double-layer windings — in which each phase is

made up of as many pole groups as poles, are called *whole-coiled* windings. They are readily distinguished from half-coiled windings because the latter are single-layer and have half as many pole groups per phase as poles. Moreover, half-coiled windings are consequent-pole, whereas whole-coiled windings are conventional when considered from the standpoint of single-phase winding theory.

Current Directions in Two-phase Windings

It is extremely important that the instantaneous currents in the coils of a polyphase winding be correct if an a-c machine is to function properly.



(*a*) Phase *A* (——) (*b*) Phase *B* (—•—•—)

FIG. 75. Coil arrangements and current directions in a 24-slot 4-pole 2-phase whole-coiled winding.

Assuming that the two or three windings in a two- or three-phase machine are displaced from each other *in space* by 90 or 120 electrical degrees, respectively, it is necessary that the pole groups be connected so that the polyphase currents create magnetic polarities that change correctly with *time*. In other words, space displacement of the windings and time displacement of the currents through the coils are essential requirements of polyphase machine operation.

Consider Fig. 75, which illustrates a 24-slot 4-pole 2-phase whole-coiled winding. The individual phases are shown in parts, with the coils located in their properly allotted slots. Assuming that phase A will have its start, S_A, in slot 1, phase B must have its start, S_B, 90 electrical degrees away; this is slot 4, three slots removed from slot 1, because there are 30 electrical degrees between slots. Now then, if the current for phase A is arbitrarily regarded as entering at S_A (a positive current, for example), the current in phase B must enter at S_B if the time displacement between phases is to be

the same as the space displacement. Thus, pole groups A_1 and B_1 will have clockwise currents, as indicated by the arrows in the slots and on the outside portions of Figs. 75*a* and *b*. *Note these current direction arrows carefully*, because the remaining arrows must be indicated with reference to those of pole groups A_1 and B_1. Since successive pole groups of coils in

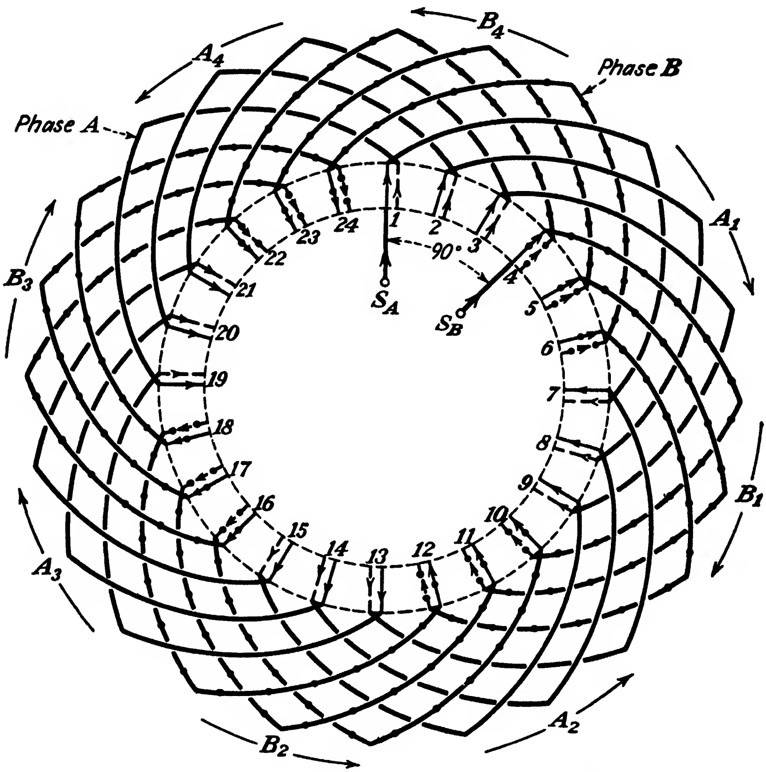


FIG. 76. Combined coil arrangements and current directions in a 24-slot 4-pole 2-phase whole-coiled winding. (See Fig. 75.)

any phase of a conventional whole-coiled winding must carry currents in opposite directions at the same instant (the magnetic polarities created by successive pole groups must be opposite), it follows that (1) for phase A the currents in A_2, A_3, and A_4 will be, respectively, counterclockwise, clockwise, and counterclockwise, and (2) for phase B the currents in B_2, B_3, and B_4 will be, respectively, counterclockwise, clockwise, and counterclockwise.

When both phases are represented on a single winding diagram, the coil arrangements and current directions appear as in Fig. 76. The following points should be noted particularly: (1) Phase A starts in slot 1, and phase

B starts in slot 4; (2) there are three coils per pole group ($24/4 \times 2$); (3) successive pole groups in each phase carry currents in opposite directions; and (4) the arrows on the outside of the diagram show that any two adjacent pole groups that carry currents in one direction are followed or preceded by two adjacent pole groups carrying currents in the opposite direction.

Once the coil arrangements and the current directions have been determined, it is theoretically immaterial how the individual coils of each phase are interconnected, so long as the currents enter at S_A and S_B and follow the arrows. Practically, however, the interconnection of the coils in a wave winding must be done in accordance with established procedures, to be discussed in subsequent paragraphs.

Current Directions in Three-phase Windings

Figure 77 illustrates a 24-slot 4-pole 3-phase whole-coiled winding, which will be analyzed in exactly the same way as was done for the two-phase winding in the foregoing article. Again, the individual phases are shown in parts, with the coils located in their properly allotted slots. Assuming that phase A will have its start S_A in slot 1, phases B and C must have their starting points S_B and S_C in slots 5 and 9, respectively; note that slot 5 is 120 electrical degrees clockwise from slot 1 and that slot 9 is 120 electrical degrees clockwise from slot 5, since, as before, there are 30 electrical degrees between slots.

Having selected the starting points for the three phases, the current directions are arbitrarily regarded as entering S_A, S_B, and S_C; this makes the time displacement between currents the same as the space displacement of the three windings. Under this condition, the current directions in the first pole groups A_1, B_1, and C_1 are clockwise. With the reference pole groups established, it is next a simple matter to indicate the current directions for the remaining ones, because successive pole groups of coils in any phase of a whole-coiled winding must create opposite magnetic polarities. Thus, A_2, B_2, and C_2 must be marked counterclockwise, A_3, B_3, and C_3 must be shown clockwise, and A_4, B_4, and C_4 must have counterclockwise arrows. These markings may be verified by referring to Figs. 77*a*, *b*, and *c*.

Figure 78 shows how the coil arrangements and the current directions appear when all three phases are combined into a single diagram. It should be carefully studied in connection with the following points: (1) Phases A, B, and C start in slots 1, 5, and 9, respectively; (2) there are two coils per pole group ($24/4 \times 3$); (3) successive pole groups in each phase carry currents in opposite directions; and (4) on the outside of the diagram *successive arrows are oppositely directed.* The latter point is especially useful to the shop man when a three-phase winding is to be connected or tested for accuracy, or when a winding diagram is to be laid out or traced.

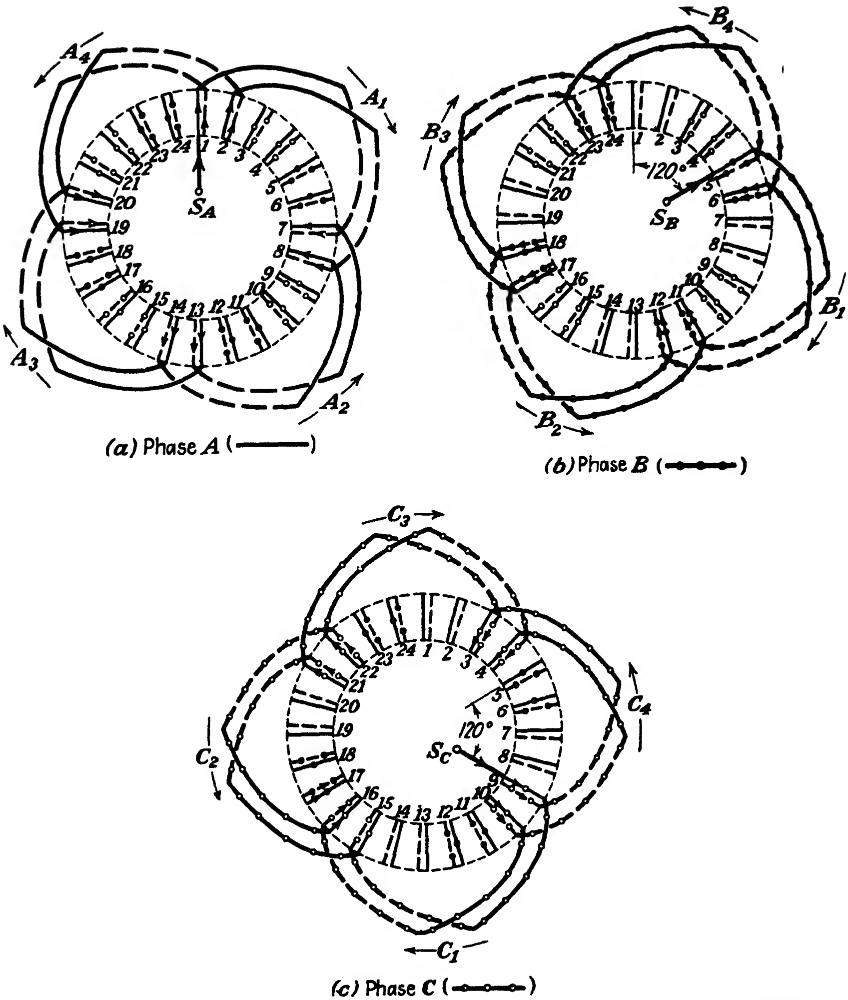


FIG. 77. Coil arrangements and current directions in a 24-slot 4-pole 3-phase whole-coiled winding.

As with a two-phase winding, once the proper coil arrangements and current directions have been established, interconnection of the various coils of any phase can proceed in a routine manner. The important thing to remember always is to follow the arrows.

Connecting the Coils of a Wave Winding

The foregoing procedure will now be extended to show how a wave winding is connected. For this purpose it will be desirable to start with Fig. 61,

which represents the coil arrangement of one phase of a three-phase winding for a 36-slot 4-pole machine. Referring to this diagram, note that each pole group consists of three, single-turn wave coils (coils per pole group $= 36/4 \times 3$); each coil is labeled with a capital letter such as A, B, C, etc., and corresponding coil ends are labeled aa', bb', cc', etc., respectively.

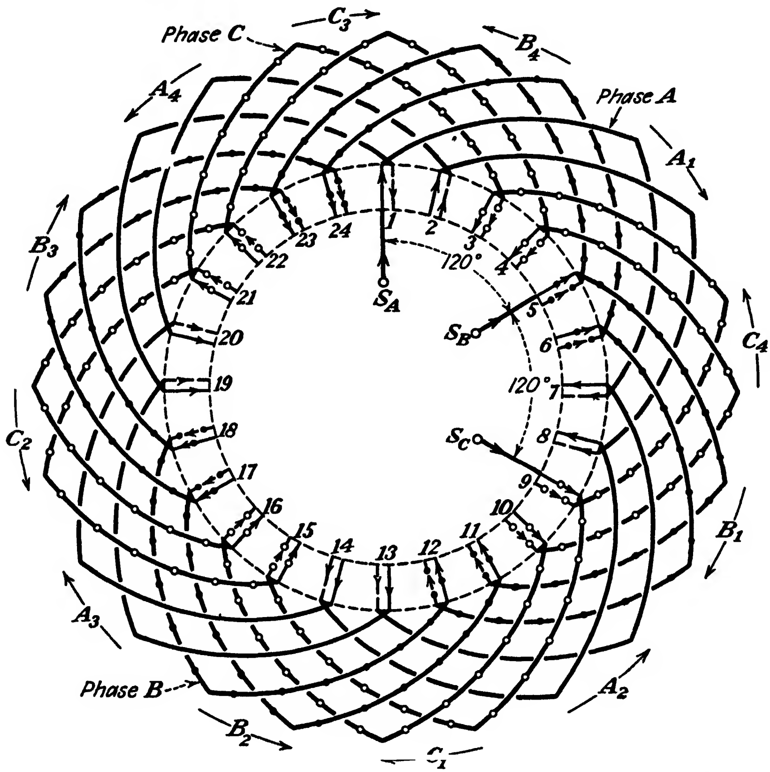


FIG. 78. Combined coil arrangements and current directions in a 24-slot 4-pole 3-phase whole-coiled winding. (See Fig. 77.)

Also observe that S_A starts at a and that the outside arrows are properly directed to conform with previous discussions.

Figure 79 represents this same phase completely connected in accordance with practices generally employed in the shop. It shows clockwise current direction for pole groups A_1 and A_3 and counterclockwise current direction for pole groups A_2 and A_4. Note that only one cross-connector R is used for the entire phase; all other coils are connected together by joining the proper bent-out coil ends where they meet.

The completed phase may be traced from S_A to F_A by advancing through the coils in the following order: (1) Start at S_A or at point a and proceed

in a *clockwise* direction through coils A, G, B, H, C, and I, ending at point i'; (2) pass along reversing connector R to point l'; (3) proceed in a *counterclockwise* direction through coils L, F, K, E, J, D, ending at point d or F_A. It is important to understand that one-half of all the coils, made up of alternate pole groups, are traced in a *clockwise* direction; the reverse

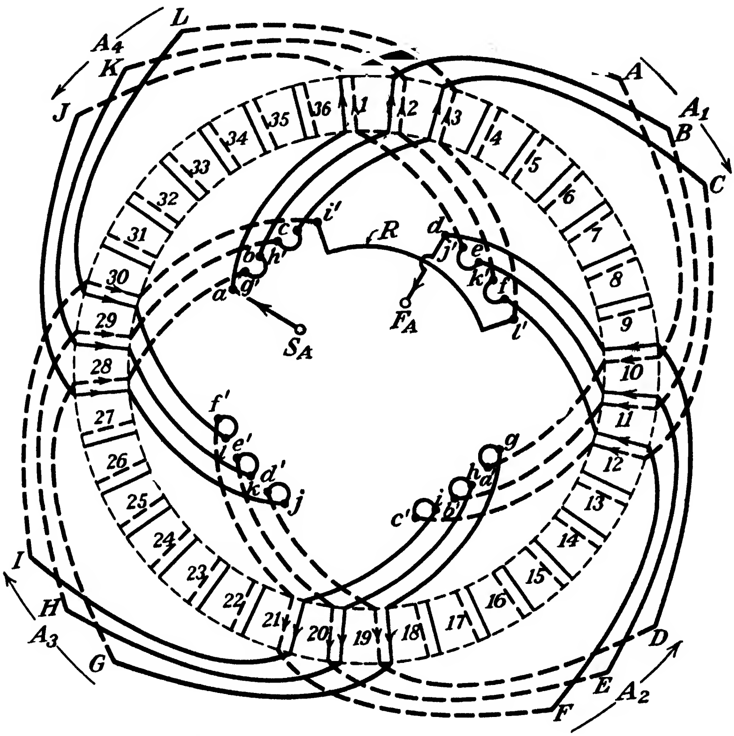


FIG. 79. Diagram showing one phase of a 36-slot 4-pole 3-phase wave winding completely connected. Note that only one cross-connector R is used. (Refer to Fig. 61 for unconnected diagram.)

connector then leads to the second half of all the coils to be traced in a *counterclockwise* direction. This tracing reversal, made possible by the reversing connector R, is absolutely necessary if the current directions through the successive pole groups of the phase are to reverse. Or, to put it another way, pole groups A_1 and A_3 carry clockwise currents and pole groups A_2 and A_4 carry counterclockwise currents only because connector R reverses one-half of the winding with respect to the other half.

Figure 80 shows the complete winding diagram, with all three phases connected in exactly the same manner as previously described. Bearing in mind the points made about phase A, the entire winding should be

traced and studied carefully. In doing so, note that phase A is drawn with continuous and broken lines, phase B with *dotted* continuous and broken lines, and phase C with *circled* continuous and broken lines. The continuous and broken lines distinguish the *top* coil-sides from the *bottom* coil-sides.

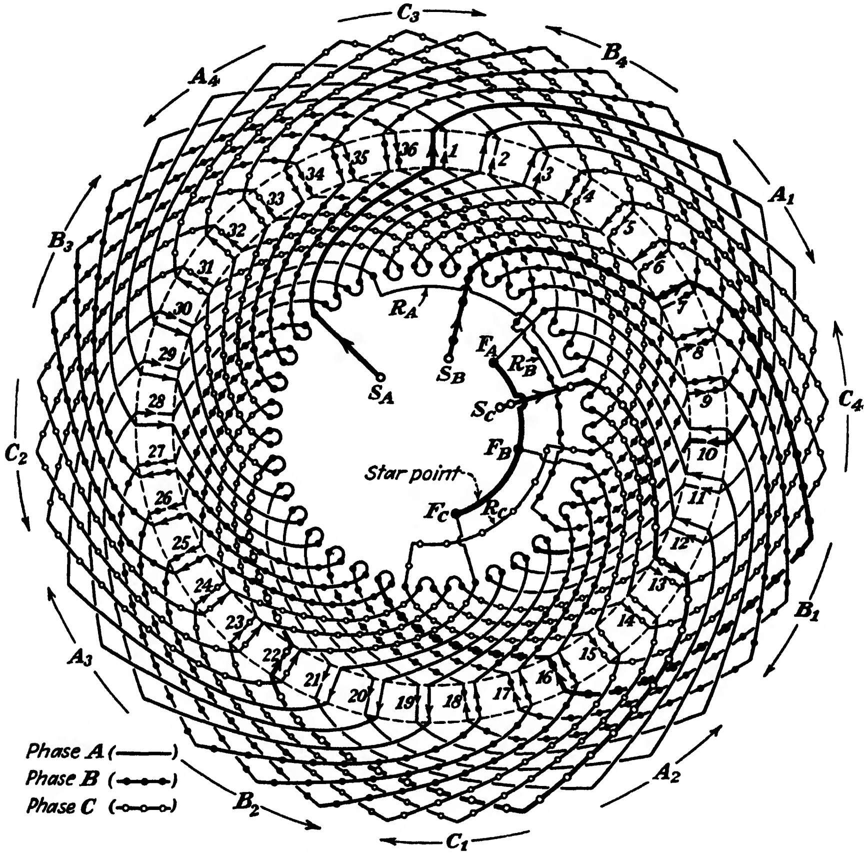


FIG. 80. Complete winding diagram for a 36-slot 4-pole 3-phase wave winding. Note that there are only three cross-connectors, R_A, R_B, and R_C, and that a star connection is used. Refer to Fig. 79 for connections of phase A only.

Figure 81 is a photograph of the start of a winding similar to that shown in the completed diagram of Fig. 80. It is on a 36-slot rotor for a 4-pole 3-phase induction motor. Each of the coils of this winding has several turns of wire, while the diagram was drawn with single-turn coils so that it may be traced more easily.

The completed rotor of Fig. 81 is depicted in Fig. 82. Note the neat, compact appearance and the three slip rings that were added after the

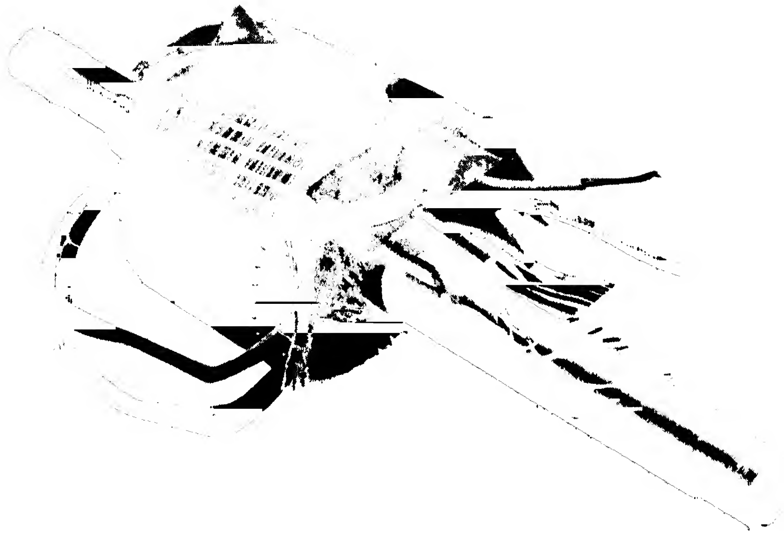


FIG. 81. Start of a 4-pole 3-phase wave winding in a 36-slot rotor for an induction motor. (*The Louis Allis Co.*)

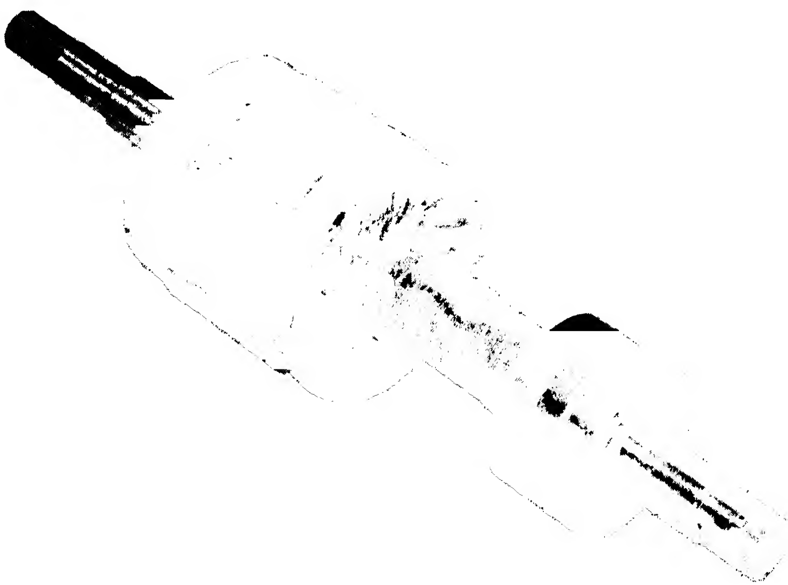


FIG. 82. Completed 4-pole 3-phase wave winding in a 36-slot rotor. The start of the winding is shown in Fig. 81, and the diagram of connections is represented by Fig. 80. (*The Louis Allis Co.*)

winding was in place. The winding ends S_A, S_B, and S_C are connected to the slip rings upon which brushes will ride when the motor is in operation.

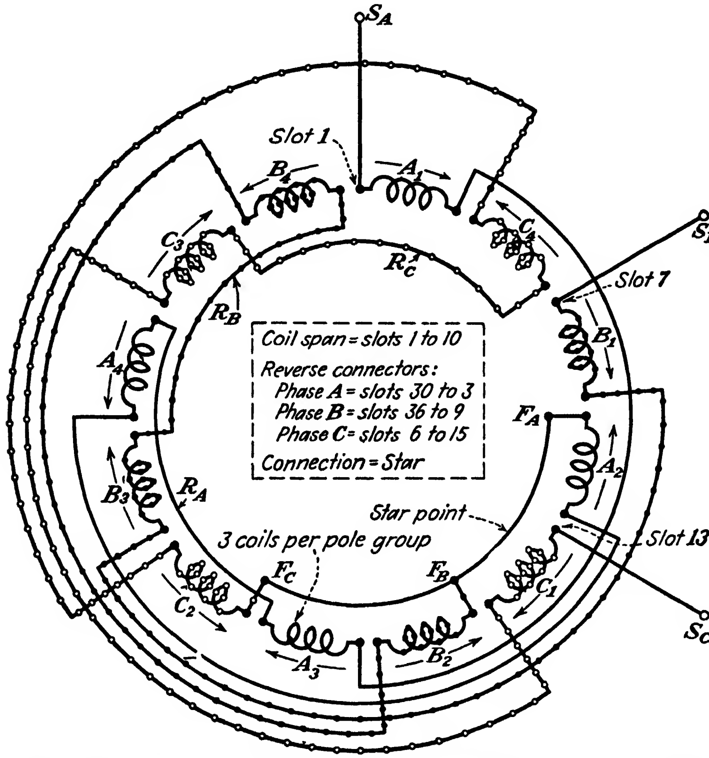


FIG. 83. Simplified diagram of a wave winding (see Fig. 80) for a 36-slot 4-pole 3-phase machine.

Simplified Diagram for Wave Windings

A thorough understanding of a complete winding diagram, such as Fig. 80, leads immediately to a simplified form similar to that given in Chap. 8 for concentric-chain windings. Although the simpler diagram does not furnish detailed information, such as coil span, connections between coils, location of the reverse connectors, locations of start and finish points, etc., it can be made to serve just as effectively if its meaning is clearly interpreted. Moreover, certain details that cannot appear on the simple drawing may be listed in a supplementary table.

Figure 83 illustrates such a diagram for the same 36-slot 4-pole 3-phase winding previously given. When studied carefully in conjunction with the complete drawing, it will be seen to have considerable merit.

A simplified schematic diagram is given in Fig. 84 for a 36-slot 6-pole 2-phase wave-wound machine. All identifying points are listed on the drawing.

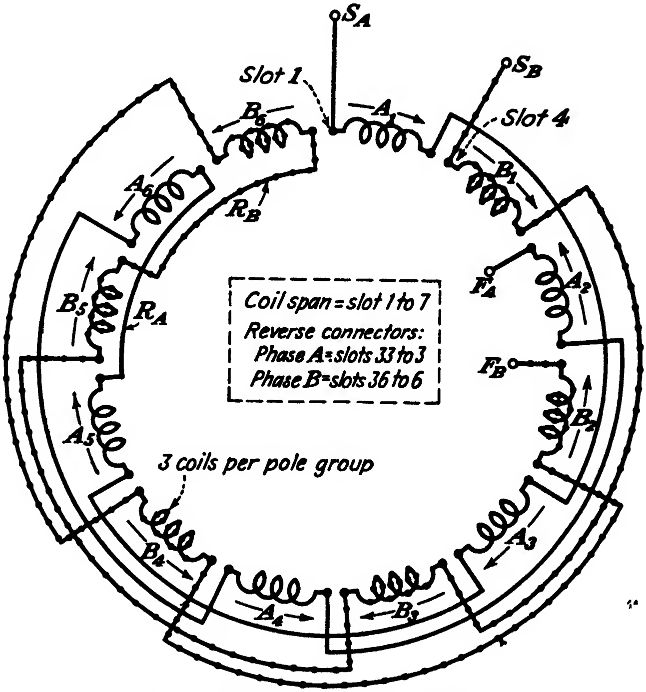


FIG. 84. Schematic diagram of a wave winding for a 36-slot 6-pole 2-phase machine.

Wave Windings with Unequal Pole Groups

In the manufacture of a-c machines, a lamination having a given number of slots is often used for windings having several pole and phase combinations. Such practice results in considerable savings in the cost of expensive dies and also saves labor.

Where the number of slots in the core can be divided by the product of poles and phases to yield an integer for several pole and phase combinations, completely symmetrical windings will be possible for all of them. This is owing to the fact that all pole groups will have the same number of coils when (slots/poles × phases) equals an integer. An excellent example is a lamination with 72 slots which will yield many three-phase and two-phase symmetrical windings. Thus, for three-phase, the number of coils per pole group will be 12, 6, 4, 3, and 2 when wound for 2, 4, 6, 8, and 12 poles, respectively. And, for two-phase, the number of coils per pole group will be 18, 9, 6, and 3 when wound for 2, 4, 6, and 12 poles, respectively.

In some winding combinations of poles and phases, it is either desirable or necessary to use a lamination in which all phases have the same number of coils, although all pole groups do not. A good illustration is a core having 90 slots, originally designed for a 6-pole 3-phase combination, that is to be wound for four poles and three phases. Since a double-layer wave winding in this core will have 90 coils, each phase contains 30 coils. Theo-

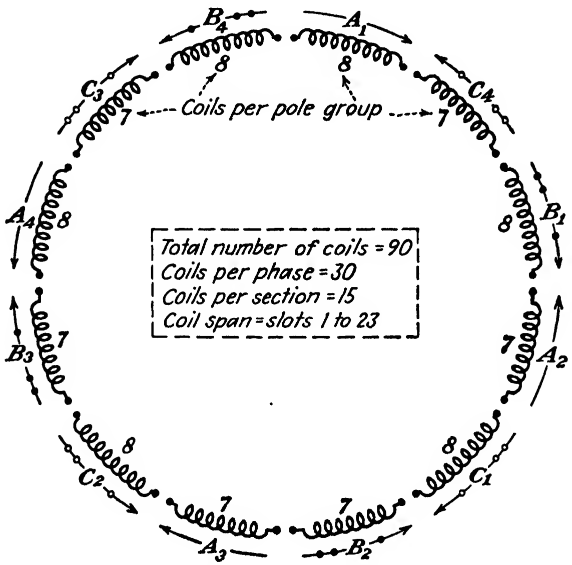


FIG. 85. Arrangement of coils for an unsymmetrical 4-pole 3-phase wave winding in a core having 90 slots. Note that the sum of the coils in each section of diametrically opposite pole groups is always 15 coils. The connections are made exactly like those in Fig. 83.

retically then, each pole group should contain $7\frac{1}{2}$ coils (30/4); but, this being impossible, two pole groups in every phase must have eight coils each and the other two pole groups seven coils each. Remembering that the coils of a wave winding are always in two sections, one section to be traced in a clockwise direction and the other section to be traced in a counterclockwise direction, the winding must be laid out with the same number of coils in each section. Moreover, the pole groups for all three phases must be planned to develop as little unbalance as possible. Figure 85 shows one arrangement of pole groups that has proven quite satisfactory. Note particularly that the sum of the coils in any two diametrically opposite pole groups is always 15 because, for this four-pole winding, each section of two pole groups must have the same number of coils.

Another example is a 48-slot core in which is placed a 6-pole 3-phase wave winding. Each phase will have 16 coils (48/3); but all pole groups

cannot have the same number of coils, because 16 coils cannot be divided equally into six parts. As a result, every phase must have four pole groups of three coils each and two pole groups of two coils each $[(4 \times 3) + (2 \times 2) = 16]$. A possible arrangement of coils and their connections is shown in Fig. 86.

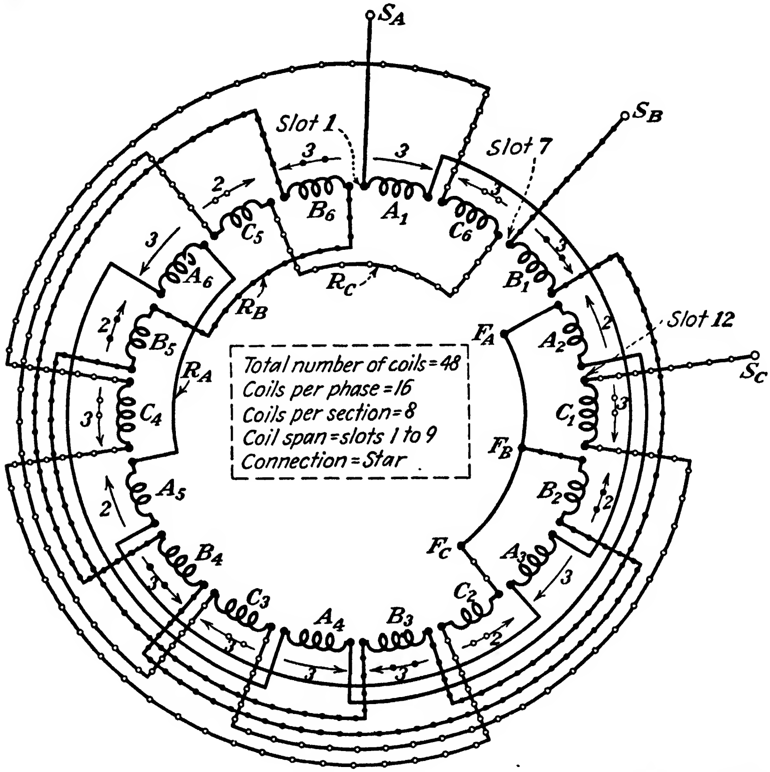


FIG. 86. Coil arrangement and connections for an unsymmetrical 6-pole 3-phase wave winding in a core having 48 slots. Note that the sum of the coils in each section of three pole groups is eight.

Summary

1. A wave winding is double-layer and has a set of coils that are all exactly alike in shape and size.

2. Wave windings are found mainly on the rotors of induction-type machines where space limitations and mechanical balance of a revolving structure have special importance.

3. The total number of coils in a wave winding is the same as the number of slots in the core.

4. A double-layer winding has as many pole groups as poles.

5. Windings having as many pole groups as poles are called whole-coiled windings. This designation distinguishes them from half-coiled windings which have half as many pole groups as poles.

6. The currents in the coils of the individual phases of a polyphase winding must be displaced, in time, by exactly the same number of degrees as they are in space, on the core. The time and space displacement must be 90 electrical degrees in 2-phase machines and 120 electrical degrees in 3-phase machines.

7. Successive pole groups of coils in any phase of a conventional whole-coiled winding must carry currents in opposite directions at the same time.

8. In 2-phase windings, any two adjacent pole groups that carry currents in one direction are followed or preceded by two adjacent pole groups carrying currents in the opposite direction.

9. In 3-phase windings, the arrows on successive pole groups are oppositely directed.

10. In wave windings, there is only one cross-connector per phase; all other coils are connected by joining the proper bent-out coil ends where they meet.

11. The coils of each phase of a wave winding are connected in two sections. Starting at S_2, one-half of the phase, consisting of coils in alternate pole groups, is traced in a clockwise direction, while the other half of the phase, consisting of the coils in the remaining pole groups, is traced in a counterclockwise direction.

12. The reversing connector R that joins the two sections of a wave winding makes it possible for the currents in successive pole groups of each phase to be in opposite directions.

13. A lamination having a given number of slots is often used for windings having several pole and phase combinations. Such practice results in considerable savings in the cost of dies and also saves labor.

14. When (slots/poles × phases) is an integer, the winding will be completely symmetrical, since all pole groups will have exactly the same number of coils.

15. In some cases laminations are used in which (slots/poles × phases) is not an integer. Under such conditions the windings will not be symmetrical, since all pole groups will not contain the same number of coils. However, when unsymmetrical windings are carefully laid out they provide satisfactory service.

CHAPTER 10

Lap Windings

The winding that is employed most widely for polyphase machines is the lap type. As was pointed out in Chap. 7, it too is double-layer and has coils that are all exactly alike in shape and size. And, like wave windings, it is whole-coiled because it has as many pole groups as poles. Since a lap winding has many design and construction advantages when used in the stators of induction motors, it has been universally adopted for such machines. It is also used frequently in the stators of alternators, although the concentric-chain winding (Chap. 8) is preferred for large-diameter, low-speed applications. This chapter, as well as several others to follow, will be devoted to a study of the principles and practices of the winding that certainly outranks the other two types numerically—the lap winding.

Connection of Coils in a Pole Group

It was previously learned that there are always as many coils in a pole group as the number of slots per pole per phase. This rule applies to both half-coiled or whole-coiled windings. In a concentric-chain winding, the coils in each pole group are always connected in series (see Figs. 65 and 68), because the machines into which this type of winding is placed generally have high-voltage ratings and, therefore, require many series turns per phase; the parallel connection of the coils in a pole group is possible but not practical. On the other hand, the coils in each pole group of a wave winding are always connected in series, because the coil construction and connection procedure automatically join together the coils in each section in this way. Finally, the coils in every pole group of a lap winding must be connected in series if an a-c machine is to operate satisfactorily, although, unlike the wave winding, a parallel connection is physically possible.

Considering the lap winding further, remember that it is double-layer, and, as such, the coils within every pole group are displaced in space. This space displacement, therefore, implies that the generated voltages in the individual coils of a pole group, although equal to each other *effectively*, will not be in time phase; they will, in fact, be out of phase by exactly the same number of degrees as the space displacement. In three-phase windings, for example, there will be two, three, and four coils per pole group

when the cores have six, nine, and twelve slots per pole, respectively. Under these conditions (see Fig. 87), the individual coils will be displaced from each other (1) by 180/6 = 30 degrees in the six-slots-per-pole core, (2) by 180/9 = 20 degrees in the nine-slots-per-pole core, and (3) by 180/12 = 15 degrees in the twelve-slots-per-pole core.

Assume next that the windings of Fig. 87 are in alternators and that the effective voltage per coil in each case is 10 volts when no load is being delivered by the machines. Now then, if the coils in each case were connected in parallel (this is done by joining a to b and a' to b' in the six-slot-

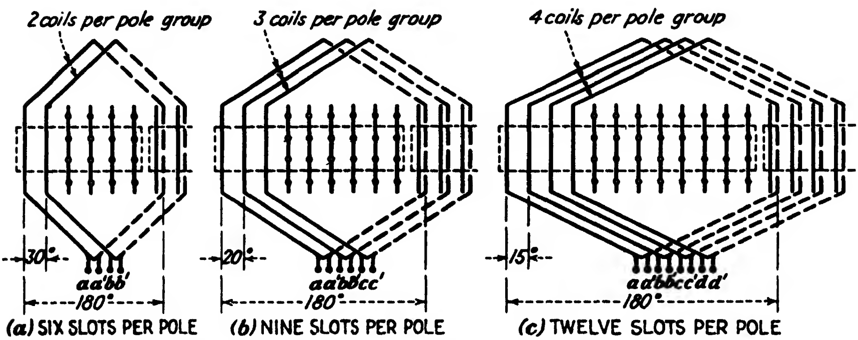


FIG. 87. Sketches illustrating phase displacements in three-phase lap windings.

per-pole sketch, a to b to c and a' to b' to c' in the nine-slot-per-pole sketch, and a to b to c to d and a' to b' to c' to d' in the twelve-slot-per-pole sketch), *internal voltages would result in the pole groups, to cause circulating currents in the parallel-connected coils.* These voltages could reach values that are as much as 5.2, 6.8, and 7.6, respectively, so that the parasitic circulating currents, apart from any load currents, could produce excessive heating in the windings. Considered from the standpoint of motor operation, the counter emf's in the individual coils of the parallel-connected pole group would be out of phase by different amounts with the impressed voltage. This would result in excessive motor heating because the coil currents would be considerably greater than normal values.

The foregoing discussion, therefore, leads to the conclusion that *the coils of all pole groups in a lap winding must not be connected in parallel.* When they are connected in series, however, there will be no circulating currents and the resulting temperature rise will be normal.

Lap Winding Coil Construction

Two general methods are used in constructing the coils of lap windings. For comparatively large machines in which the core has open slots, the individual coils are preformed on special equipment, after which they are

taped. Sometimes they are dipped in an insulating varnish and baked, although more often the dipping and baking operation of the completed stator is performed after the winding is in place. Figure 88 shows a photograph of a lap coil in two stages of construction. In the illustration to the

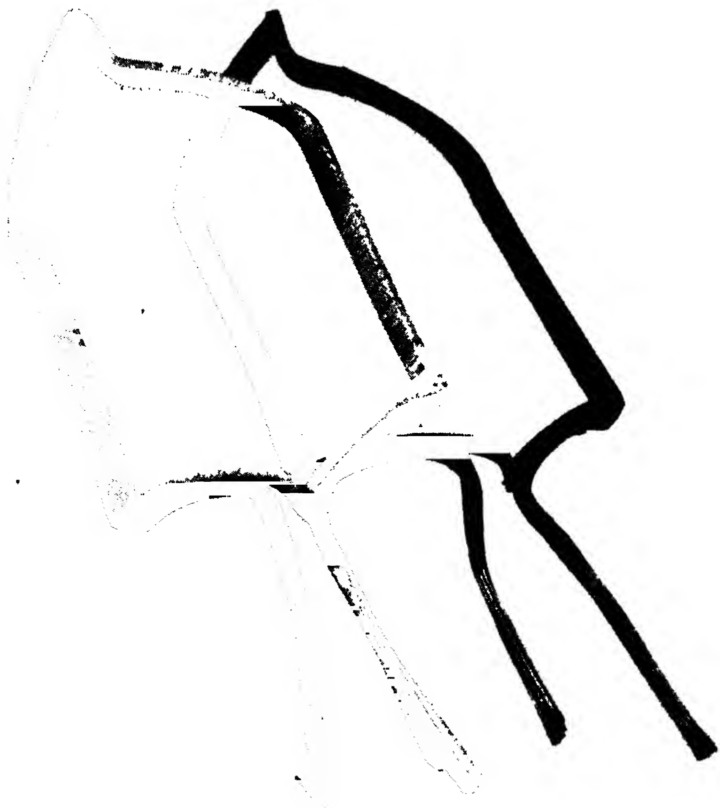


FIG. 88. Form-wound two-turn lap coil shown in two stages of construction. Note that the conductor is made up of several parallel wires. (*The Louis Allis Co.*)

right may be seen the untaped two-turn coil where the conductor is made up of several stranded rectangular wires; the illustration on the left shows a similar coil completely taped and ready for use.

For the smaller machines, and particularly in those having cores with partially closed slots, all the coils in a pole group are wound on a gang mold with a continuous single wire. The coils are, therefore, automatically connected in series, so that no connecting and soldering operations are

required within each pole group. Figure 89 illustrates a three-coil gang for one pole group of a 36-slot 4-pole 3-phase lap winding. Also illustrated are insulation materials for the slots and the cotton tape that is used around the end connections of the coils after the latter are inserted in the slots. As was previously explained, untaped coils of this construction are fed into the slots, one or two wires at a time, between the narrow spaces separating the overhanging teeth.

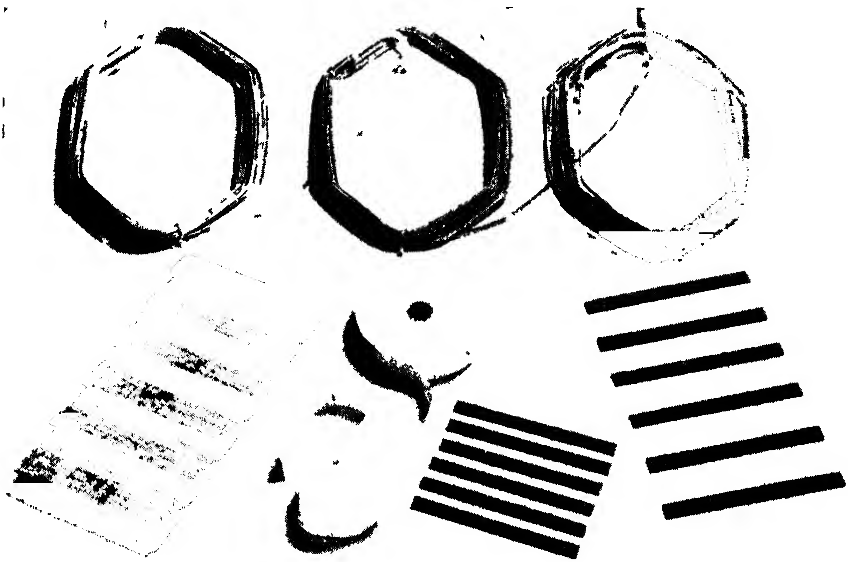


FIG. 89. Three-coil gang for one pole group of a lap winding. Insulation materials for slots and coils are also seen (*The Louis Allis Co.*)

Current Directions and Pole-group Connections in Lap Windings

Since lap windings are double-layer, and therefore whole-coiled, the current directions in successive pole groups of each phase must be opposite. This follows directly from what was said concerning wave windings in Chap. 9, where it was shown that the magnetic polarities created by successive pole groups must be opposite. Moreover, when the simplified wiring diagrams are drawn for lap windings, they will be found to be quite similar to those drawn for wave windings. As a result (1) in two-phase windings, the arrows on the outside of the diagram show that any two adjacent pole groups that carry currents in one direction are followed or preceded by two adjacent pole groups carrying currents in the opposite direction, and (2) in three-phase windings, successive arrows on the outside of the diagram are oppositely directed.

Connecting the Coils of a Lap Winding

To understand how a lap winding is connected, it will be desirable to start with Fig. 63, which illustrates the coil arrangement for one phase of a three-phase four-pole winding in a 36-slot core. Note that there are four pole groups, in each of which are three coils (coils per group = 36/4

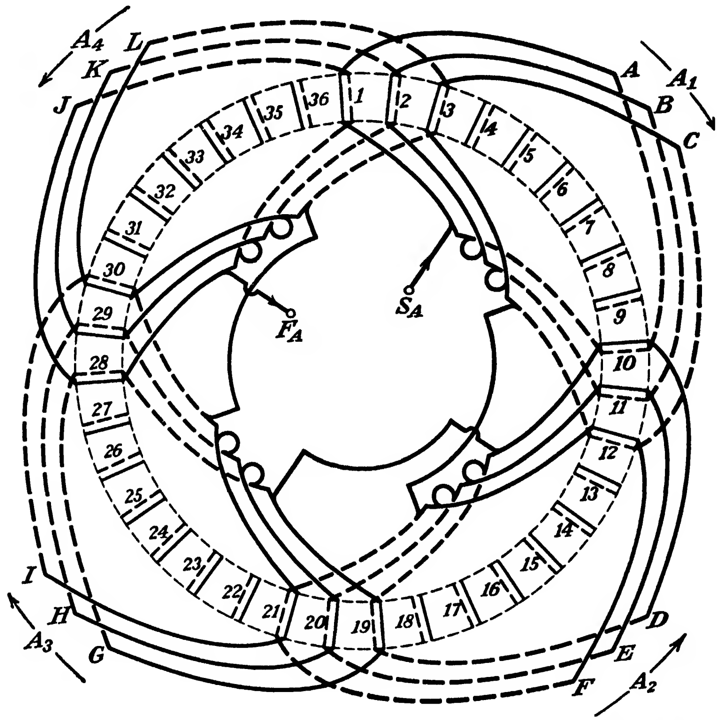


FIG. 90. Diagram showing one phase of a 36-slot 4-pole 3-phase lap winding completely connected. (Refer to Fig. 63 for unconnected diagram.)

× 3). Each coil, labeled with a capital letter such as A, B, C, etc., is drawn to indicate that there are several turns of wire, and with the wire ends emerging at the bottom center.

Figure 90 represents the same phase completely connected. This was done first by joining the three coils in each pole group in series, and then by connecting the four pole groups in series so that successive pole groups carry currents in opposite directions. Tracing the phase from its starting point S_A in slot 1, observe that the currents in the coils of the first and third pole groups A_1 and A_3 are clockwise, while those in the second and fourth pole groups A_2 and A_4 are counterclockwise.

Figure 91 shows the complete winding diagram, with all three phases

connected in exactly the same manner as previously described. In tracing the diagram, it should be noted that phase A is drawn with continuous and broken lines, phase B with *dotted* continuous and broken lines, and phase C with *circled* continuous and broken lines. The delta (Δ) connec-

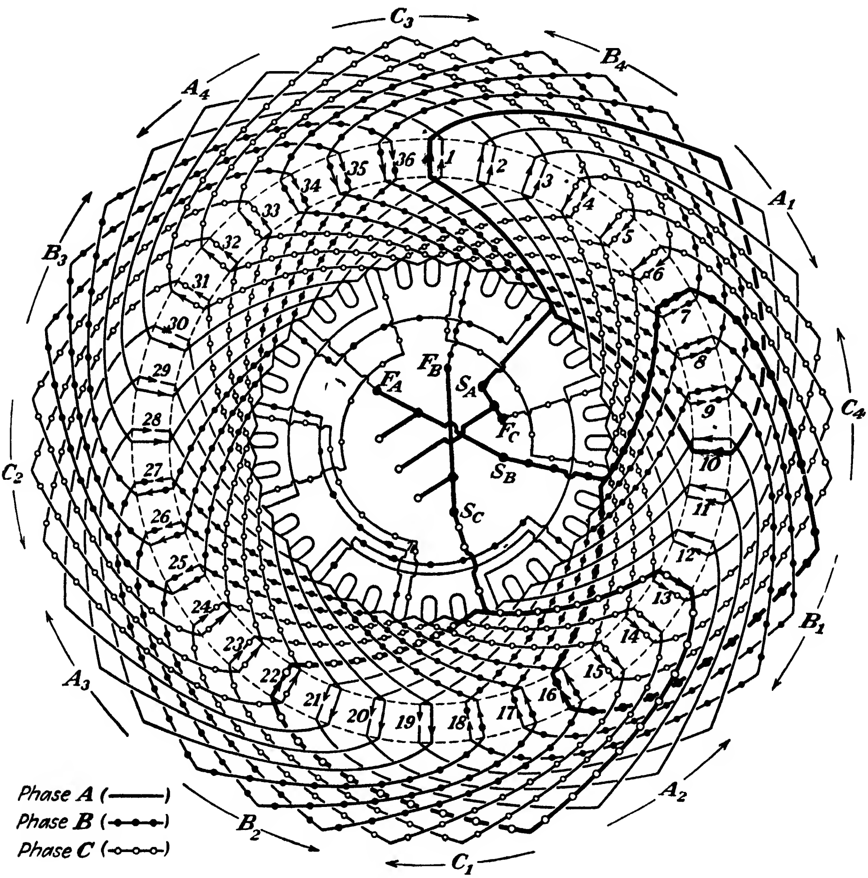


FIG. 91. Complete winding diagram for a 36-slot 4-pole 3-phase lap winding. The phases are interconnected in delta (Δ) with the line terminals as the junctions of F_A and S_B, F_B and S_C, and F_c and S_A. Refer to Fig. 90 for connections of phase A only.

tion was selected for this winding, so that the line terminals are the junctions of F_A and S_B, F_B and S_C, and F_C and S_A. Also, the starting points of phases B and C are slots 7 and 13, respectively. Attention is again called to the fact that successive arrows on the outside of the drawing are oppositely directed; furthermore, the pole groups designated with odd subscripts have clockwise arrows, while pole groups with even subscripts have counterclockwise arrows.

After the detailed winding diagram has been studied and thoroughly mastered by the student, its simplified counterpart may be used thereafter to adequately represent lap windings having any combination of slots, poles, and phases. Moreover, the simpler drawing lends itself particularly well to the analysis of paralleled and two-speed windings, to be considered later. To illustrate further the 36-slot 4-pole 3-phase delta-connected

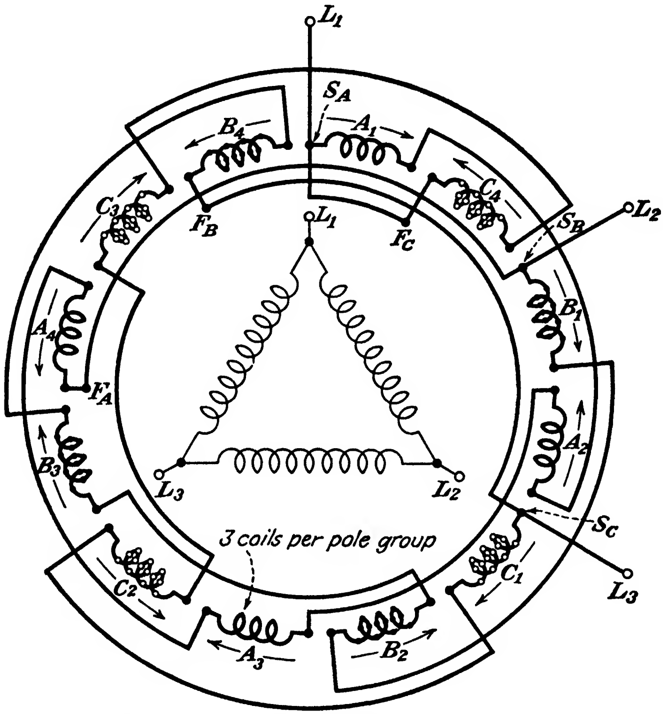


Fig. 92. Simplified diagram of a lap winding (see Fig. 91) for a 36-slot 4-pole 3-phase machine.

example, Fig. 92 is given. It is best understood when analyzed in terms of the completely developed winding diagram Fig. 91.

Comparing the complete wave and lap winding diagrams of Figs. 80 and 91, it is at once apparent that the latter has many more cross-connectors, *i.e.*, connections between pole groups, than the former; in fact, the lap winding has nine while the wave winding has three. Moreover, in practice the cross connections are made after all the coils have been installed and joined together into pole groups. The job of connecting the pole groups should, of course, be done carefully and accurately, because it is this operation in the winding installation that usually determines whether or not a

FIG. 93. Photograph of an operator making the cross connections in a lap winding. (*Reliance Electric and Engineering Co.*)

machine will perform satisfactorily. Figure 93 depicts an operator making the cross connections in a lap-wound stator.

Interconnecting Pole Groups in Lap Windings

In double-layer lap windings, every series-connected pole group of coils has two ends, one of which emerges from a coil-side in the top of a slot, and the other from another coil-side in the bottom of a slot. When the coils are formed like those illustrated by Figs. 62 and 88, the left end is a *top* and the right end is a *bottom*. An alternate coil design places the right coil-side in the top of one slot and the left coil-side in the bottom of another; in such cases the left end of a series-connected pole group of coils will be a *bottom* and the right end will be a *top*. Although the first of these has been arbitrarily selected for the drawings of this book, both schemes are employed in practice.

Two general methods are used to interconnect the pole groups of each phase in lap windings. These are (1) the top-to-top (T–T) and bottom-to-

bottom (B–B) connection and (2) the top-to-bottom (T–B) and bottom-to-top (B–T) connection.

1. *The T–T, B–B connection.* In this connection method, the pole groups of each phase are joined together in *regular succession*, as illustrated

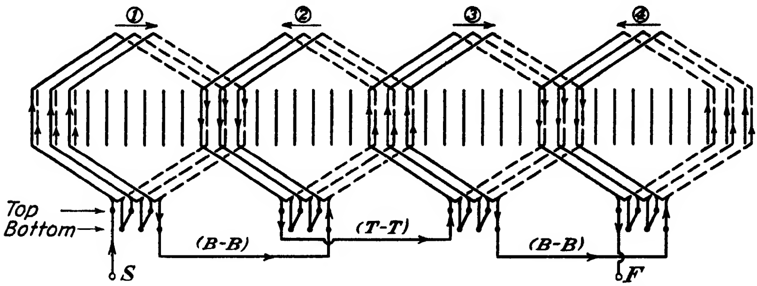


FIG. 94. Sketch illustrating how the pole groups of one phase of a lap winding are connected with *bottom-to-bottom* (B–B) and *top-to-top* (T T) connectors.

by Fig. 94. Following the arrows from *S* to *F*, it will be observed that the magnetic polarities of successive pole groups will be opposite only if the *T–T* and *B–B* connections are used.

2. *The B–T, T–B connection.* In this connection method, the pole groups of each phase are joined together in *alternate succession.* This implies that

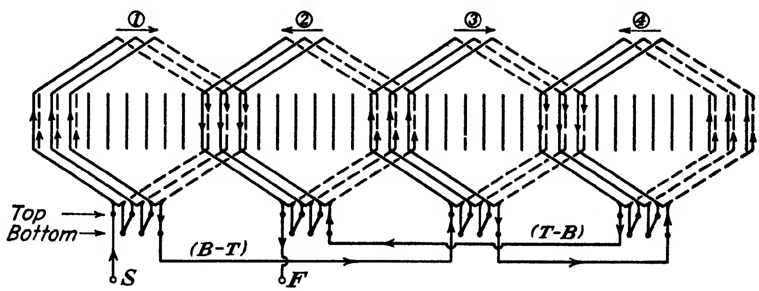


FIG. 95. Sketch illustrating how the pole groups of one phase of a lap winding are connected with *bottom-to-top* (B–T) and *top-to-bottom* (T B) connectors.

one half of the coils, made up of alternate pole groups and carrying current in one direction, are first connected in series; the other half of the coils, made up of the remaining alternate pole groups and carrying current in the opposite direction, are next joined in series and to the first section. Figure 95 shows how this is done for the four pole groups of one phase of a lap winding.

From the foregoing discussion it should now be clear that the T–T, B–B connection method was used in Figs. 91 and 92.

To extend the B–T, T–B connection method to include all phases of a three-phase lap winding, Fig. 96 is given. It is for a six-pole three-phase machine having a 54-slot core, with the phases connected in star.

It is always important to remember that the arrows indicating the current directions in the coils of the various pole groups are exactly the same, regardless of which connection method is used. In fact, any desired se-

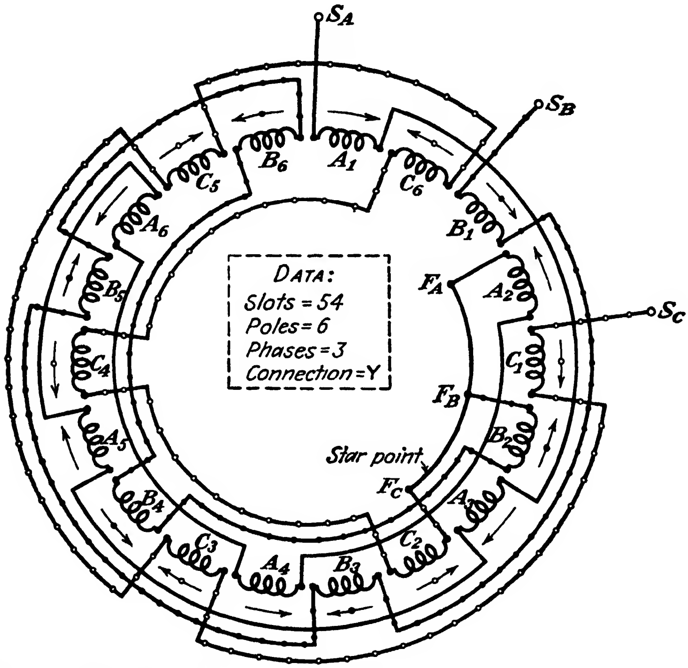


FIG. 96. Simplified winding diagram illustrating the B–T, T–B connection method for a lap winding.

quence may be employed in connecting the pole groups together if the arrows are carefully followed. However, since systematic procedures are generally preferable in making complex winding connections, the methods outlined have become standard in practice.

Termination of the Line Wires

It is customary to bring out the line terminal wires from the winding through a junction box conveniently fastened to the frame of the machine. In practice this is usually done by terminating the winding at points that are as close to the junction box as possible, because the line leads can then be comparatively short. Remembering that the correct space displacement between the phases is determined solely by the proper current directions

through the coils of the various pole groups, it should be apparent that the location of the terminal points is entirely immaterial so long as the correct arrow directions are followed.

The rule that should always guide the operator, when *the line terminal* points are selected, is that the points *must always be traced into the first*

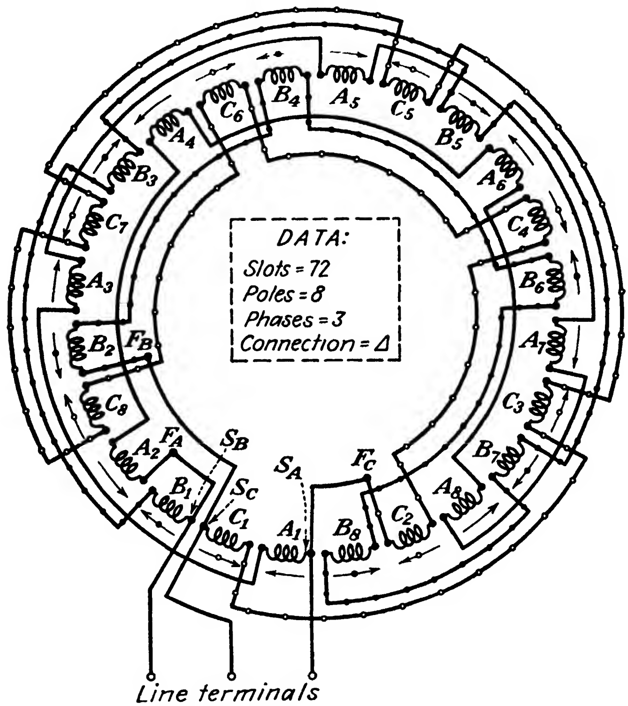


FIG. 97. Simplified lap winding diagram illustrating how the three line terminal leads are brought out from three successive pole groups. The T-B, B-T connection method is used.

pole groups of the respective phases in the direction of the arrows. Assuming that the starting points are properly chosen at the arrow tails, the first pole groups may be located in any part of a winding.

In a three-phase winding the three line terminal wires may be brought out in two possible ways. In the first of these, the one that has consistently been used thus far, they are brought out from the arrow tails of *three alternate pole groups.* This may be noted in Figs. 96, 92, 86, and 83. Of course, the three alternate pole groups could just as well have been at either side of the core or at the bottom. In the second scheme the three line terminals may be traced to the arrow tails of *three successive pole groups.* Figure 97 shows such an arrangement for an eight-pole three-

phase delta-connected lap winding in a 72-slot core; the T–B, B–T connection method is used to further illustrate the previous article.

Insulating the Winding

All electrical machines consist essentially of three kinds of material (1) copper wire, (2) iron, and (3) insulation. When current passes through the copper armature winding, magnetic flux is created in definite symmetrical patterns in the iron and air spaces. If an armature winding is to function properly, the individual copper conductors must be thoroughly insulated from neighboring conductors in the same coil, from conductors in other coils, and from the iron, generally referred to as *ground*. Figure 89 depicts several kinds of insulating material commonly employed for the winding of a-c machines.

Since insulation serves no electrical or magnetic purpose, it is used as sparingly as possible. In other words, any reduction in the thicknesses of the insulating materials makes additional space available for a larger cross-sectional area of copper, with a resulting increase in the output of a given machine. Moreover, heat is dissipated more readily when the amount of insulation is reduced, and this leads to cooler operation. On the other hand, inadequate or poor insulation tends to subject the armature winding to severe electrical stresses that may lead to complete breakdown. It should be clear then that, among other things, a well-designed machine utilizes quality and quantity of insulation to such advantage that output is high, temperature rise low, and continuity of service long.

Before an operator is ready to install a winding in a core, properly shaped insulating cells must be inserted in the slots; these are made of extremely high-quality materials such as special papers and varnished cambric. Since the voltage between winding and ground is a maximum, the slot cells usually have dielectric strengths in excess of 1,000 volts plus twice the rated voltage of the machine; this is in accordance with A.I.E.E. standards. The insulation on the wire itself may be enamel, *Formvar* or *Formex,* cotton coverings, or combinations of these; the wire insulation is generally adequate to withstand the low voltage between wires in the same coil and, in the end connections, wires in different coils in the *same* pole group. Where the wires in adjacent coils of *different* pole groups are likely to touch in the end connections, the voltage is generally higher than the wire insulation can tolerate; extra insulation is, therefore, needed between such coils. This so-called *phase insulation* is usually a strip of high-grade varnished cambric placed between every two adjacent coils in different pole groups or phases.

Figure 98 illustrates a partially completed lap winding in the core of an induction motor. Clearly visible and extending out from the slots are

FIG. 98. Partially completed lap winding in the stator core of an induction motor. Note particularly the slot, wire, and phase insulations. (*The Louis Allis Co.*)

the carefully shaped slot cells, which form a cushion for the bent coils, the wire insulation, and the phase insulation, the latter to be trimmed later when the winding is completely installed.

After the entire winding is in place and connected, it is the practice to dip the entire assembly into a hot insulating varnish and bake it for several hours in an oven. This operation adds further insulation and mechanical strength to the winding and protects it against the effects of water, oil, dirt, fumes, and other destructive elements. Figure 99 shows the completed stator of Fig. 98, after the dipping and baking treatment and ready to be pressed into its housing.

Summary

1. The lap winding is the type most widely used in the stators of polyphase machines.
2. A lap winding is double-layer and has coils that are all exactly alike in size and shape.

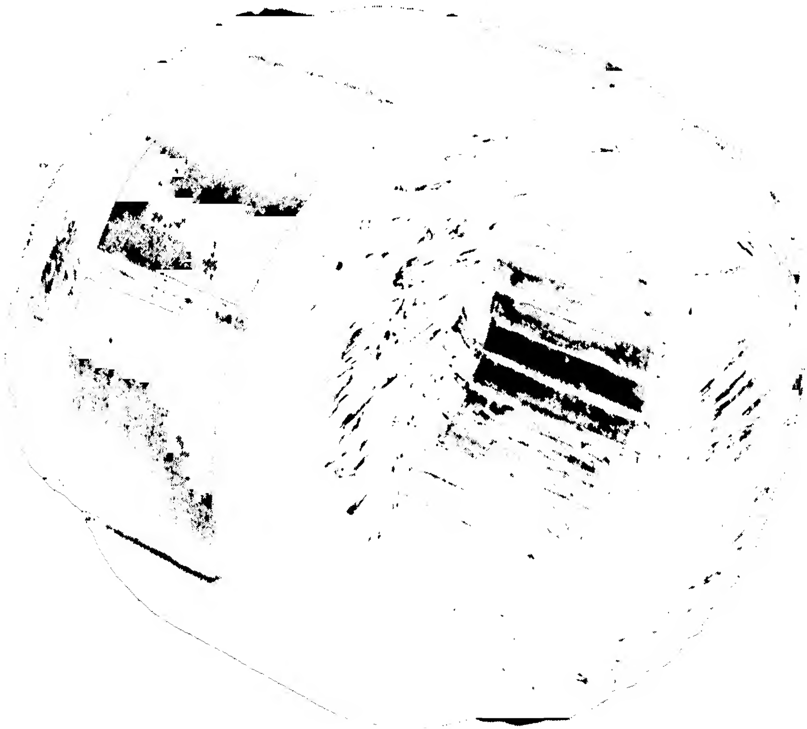


FIG. 99. Completed stator of Fig 98 after the dipping and baking treatment. (*The Louis Allis Co.*)

3. The coils in each pole group of a concentric-chain winding are generally connected in series, although it is possible to join them in parallel.

4. The coils in each pole group of a wave winding are always connected in series, because the coil construction and connection procedure automatically join together the coils in each section in this way

5. The coils in each pole group of a lap winding must be connected in series if an a-c machine is to operate satisfactorily; a parallel connection is physically possible but not practically permissible.

6. The coils in each pole group of a lap winding must not be connected in parallel because their effective voltages, although equal, are not in time phase with each other.

7. When the coils of each pole group of a lap winding are connected in series, as they should be, there will be no circulating currents, and normal heating will result in the machine.

8. For rather large machines in which the cores have open slots, the coils of lap windings are preformed and taped.

9. For comparatively small machines, or those having cores with partially closed slots, the coils for lap windings are usually wound on a gang mold. Each gang consists of the coils in one pole group, all wound with a single continuous wire.

10. Successive arrows on the diagram of a three-phase winding must be oppositely directed.

11. A lap winding has $(P - 1)$ cross-connectors per phase compared with only one for the wave winding.

12. Two schemes are used in interconnecting the pole groups of lap windings. They are (1) the top-to-top (T–T) and bottom-to-bottom (B–B) connection and (2) the top-to-bottom (T–B) and bottom-to-top (B–T) connection.

13. In the T–T, B–B connection method, the pole groups of each phase are joined together in regular succession.

14. In the T–B, B–T connection method, the pole groups of each phase are joined together in alternate succession.

15. The line terminal points may be brought out from any part of a polyphase winding. However, the line terminals must be selected so that they are traced into the first pole groups of the respective phases in the direction of the arrows.

16. All electrical machines consist essentially of three kinds of material: (1) copper wire, (2) iron, and (3) insulation.

17. The amount and quality of insulation chosen for the various parts of a machine should be adequate to protect the windings from breakdown. Too much insulation, however, limits the output of a machine and tends to increase the temperature rise.

CHAPTER 11

Winding Connections for Different Voltages

It is sometimes necessary to change the winding connections of an a-c machine so that it will operate at a different voltage from the one for which it was originally designed. More often manufacturers bring out proper leads from the winding so that a motor may be connected for operation at either of two different voltages, one of which is usually twice the other. To understand how winding connection changes affect operating voltages, certain fundamental principles must be recognized. This chapter will concern itself with a detailed discussion of these principles.

Voltage per Pole Group

When an a-c winding is designed, the total number of turns of wire in each phase is determined by the operating voltage across that phase. This implies that *the correct voltage per turn is established and must not be changed, no matter what other changes are made.* Thus, if a 440-volt motor is to be used on a 220-volt circuit, the winding connections must be altered correspondingly, so that the established voltage across each turn of wire is maintained when the lower line potential is applied. Assuming that all the turns in a phase are connected in series, it follows that the volts per turn are equal to the volts per phase divided by the turns per phase. Remembering that each phase is made up of pole groups, in each of which the coils are always connected in series, it must be true that the volts per pole group is fixed by the original winding design. This leads to the first fundamental principle concerning all winding and voltage changes, which may be stated as follows: *Whenever the voltage across a machine is changed, the winding connections must be changed so that the original volts per pole group remains unaltered; conversely, whenever the winding connections are changed, the impressed line voltage must be changed so that the original volts per pole group remains unaltered.* The same principle applies equally well to alternators, except that winding changes always affect the line voltage available at the terminals of the machine.

An example should make this clear. Assume a four-pole delta-connected 440-volt lap-wound motor, in which the four pole groups of each phase are connected in series. The winding connections are given in Fig. 92.

Under these conditions the voltage per pole group is $440/4 = 110$. To use this motor on a 220-volt source, the four pole groups of each phase would have to be connected into two parallel paths because the voltage per pole group would remain 110 only if this were done. Moreover, the motor could also be operated satisfactorily from a 110-volt source if the four pole groups of each phase were connected into four parallel paths, since the volts per pole group would remain 110 in this case also. Figure 100 shows schematically how the foregoing winding changes are made for one of the three phases. Note particularly that the arrow directions are

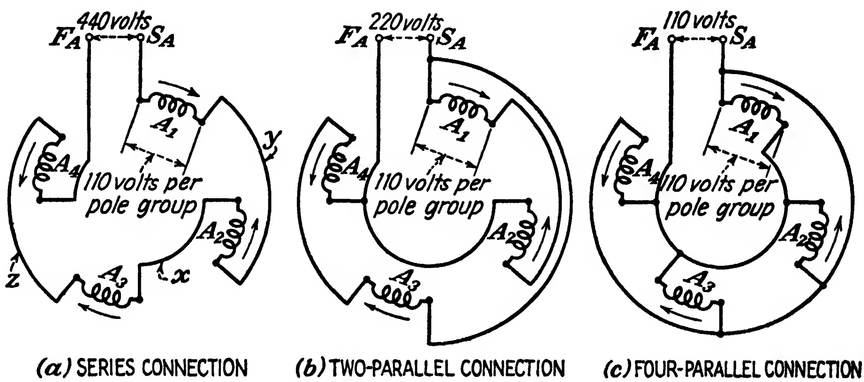


FIG. 100. Sketches illustrating how the pole groups of one phase of a three-phase winding should be connected for three different phase voltages. Note particularly that the number of volts per pole group is the same for all connections.

exactly the same for all three connections. The same changes would obviously be made for the other two phases, and the proper S and F points would be joined together to form the delta. It should be pointed out that each pole group would create equal fluxes regardless of the connection, because the volts per pole group remains unchanged.

In the actual machine, a series-connected winding can readily be changed to a two-parallel connection by cutting the wire at x (Fig. 100a) and joining the A_3 and A_2 ends to S_A and F_A, respectively; corresponding changes are then made in the other two phases. To modify a series-connected winding to a four-parallel connection, wires would also have to be cut at y and z; the A_2 and A_4 ends are then joined to S_A, while the A_1 and A_3 ends are joined to F_A.

To further illustrate the two-parallel connection for all three phases of a four-pole delta winding, Fig. 101 is given. The diagram may be readily studied if each phase is traced, through two parallel paths, from its start S to its finish F.

A schematic diagram showing how the four-parallel delta connection

is made is illustrated by Fig. 102. Here again each phase should be traced separately from its start to its finish, the line terminals being the junctions of F_A and S_B, F_B and S_C, and F_C and S_A.

At this point, mention should be made of the fact that any parallel-connected winding must always have the same number of series pole groups

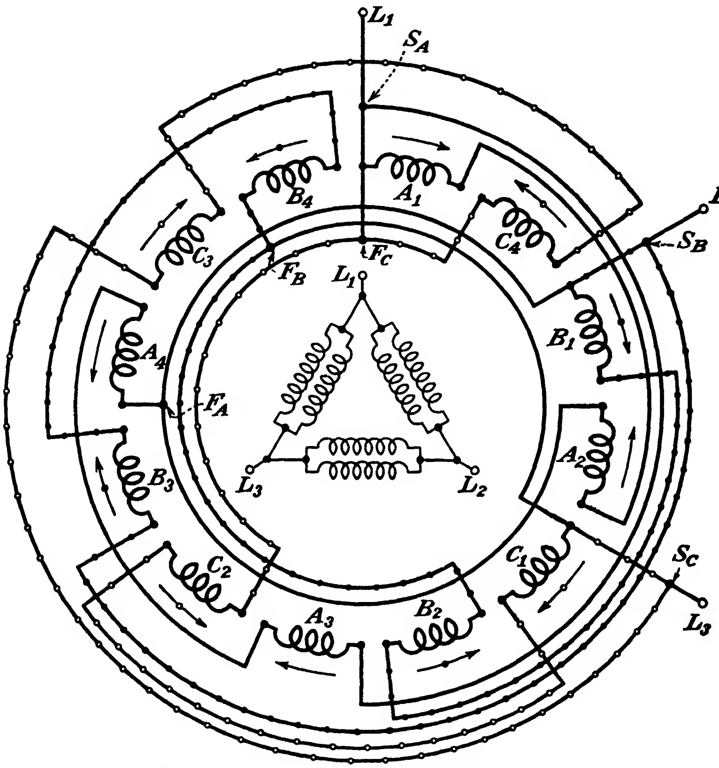


FIG. 101. Schematic diagram of a 4-pole 3-phase two-parallel delta-connected winding. See Fig. 92 for the series-connected delta diagram.

in each of the parallel paths. This is obviously true because the voltage across all pole groups can be the same only under this condition. Thus, a six-pole winding can have a two-parallel, a three-parallel, and a six-parallel connection; it cannot have a four- or five-parallel connection. Further, an eight-pole winding can have two-, four-, and eight-parallel connections; there can be no three-, five-, six-, or seven-parallel connections.

The Dual-voltage Winding

A common practice among manufacturers of three-phase induction motors is to bring out nine terminal leads from the winding so that the

latter may be connected for operation on either of two voltages, one twice the other. From what has already been learned concerning winding and voltage changes, it should be evident that the series connection could be used for the higher potential and that the two-parallel connection should be used for the half-voltage rating. This is exactly the procedure that is

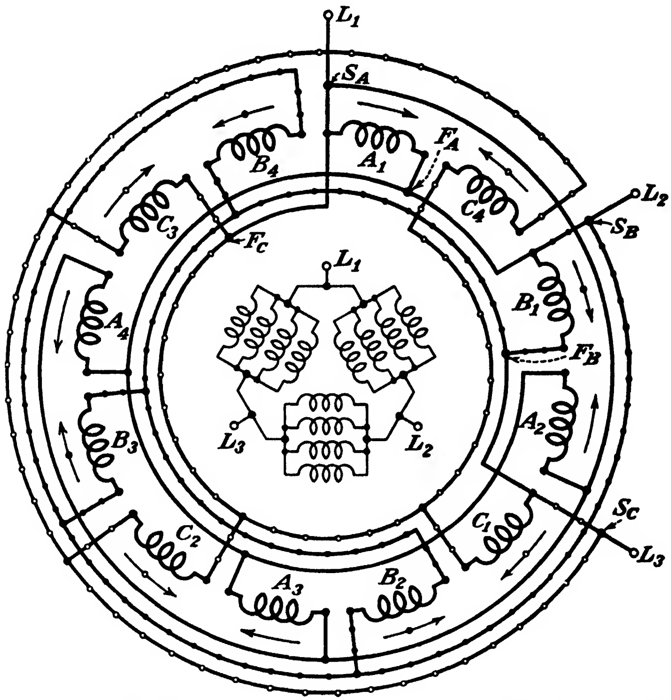


FIG. 102. Schematic diagram of a 4-pole 3-phase four-parallel delta-connected winding. See Fig. 92 for the series-connected delta diagram.

employed with the series-*star* and two-parallel *star* interconnections of the three phases as more practical than the delta. To accomplish this, each phase is split into two halves and leads are brought out from the winding, as illustrated by Fig. 103*a*. Then, if the leads are joined as shown in Fig. 103*b*, the series-star—higher voltage connection—is made; the two-parallel —lower voltage connection—is made as shown by Fig. 103*c*. Note that the volts per pole group remain the same for both the series-star and two-parallel star arrangements because the voltage per phase is twice as much in the former as in the latter.

Of course, the actual winding connections must follow the standard practice which requires definite current directions through the coils of the

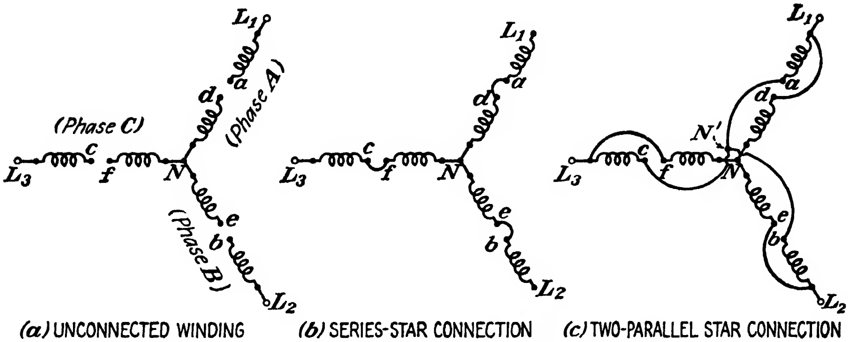


FIG. 103. Sketches illustrating the winding connections for a dual-voltage motor.

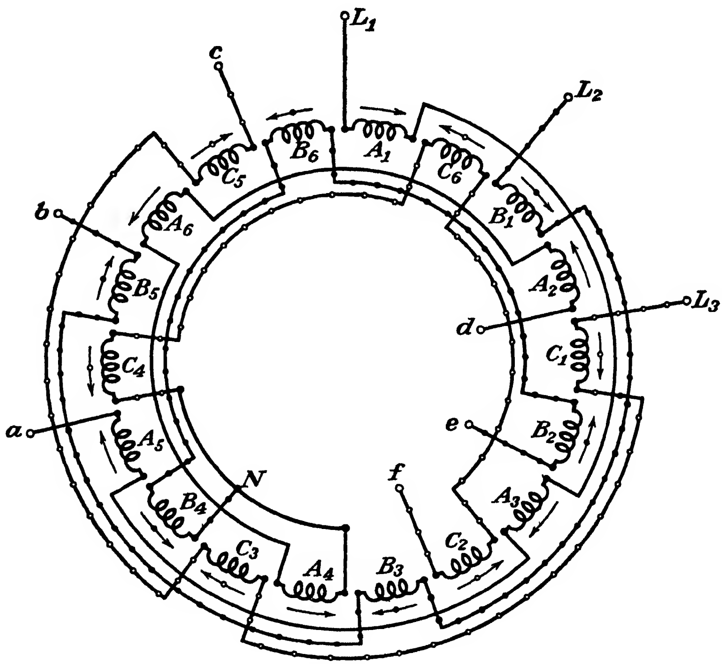


FIG. 104. Schematic diagram of a 6-pole 3-phase dual-voltage winding. See Fig. 103 for sketches showing how the series-star and two-parallel star connections are made. (The B–T, T–B connections method is used here.)

various pole groups. This is indicated by Fig. 104 for a six-pole three-phase winding, where the terminal leads are marked in exactly the same way as they appear in the simplified sketches of Fig. 103.

Analyzing the two figures, note the following: (1) For the series-star

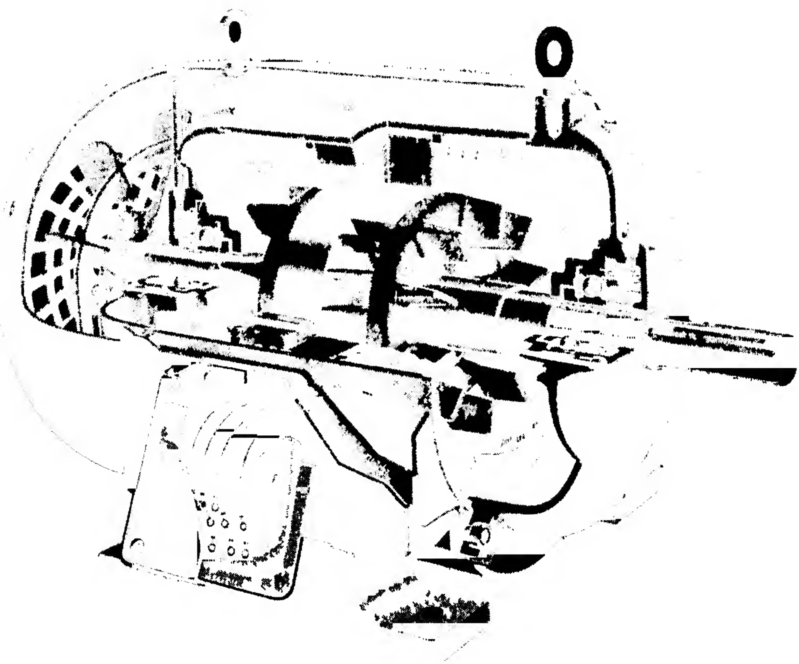


FIG 105 Cutaway view of a three-phase induction motor in which nine terminal leads are brought out to be connected for either of two voltages. See Fig 104 for diagram of connections (*Reliance Electric and Engineering Co*)

connection, the two halves of each phase are joined in series by connecting a to d, b to e, and c to f, thus the neutral or star point N is permanently made inside the machine, (2) for the two-parallel connection, the two halves of each phase are joined in parallel by connecting d to L_1, e to L_2, f to L_3, and a to b to c, to form a second neutral point N'; this latter neutral point N' is at the same electrical potential as the permanent neutral point N, so that the two need not be connected together as is customary when the winding is internally connected two-parallel star.

Figure 105 shows a cutaway view of a dual-voltage squirrel-cage induction motor in which the nine terminal leads that come out from the winding are clearly visible.

Parallel-winding Transformations and Voltage Changes

Table 2 lists all the possible parallel combinations in 2- to 16-pole motor windings, and the corresponding relative voltages as a percentage of the series-connected voltage when a change is made from one to another.

TABLE 2. VOLTAGES OF PARALLEL-CONNECTED WINDINGS AS A PERCENTAGE OF A SERIES-CONNECTED WINDING

Connection	No. of poles							
	2	4	6	8	10	12	14	16
Series	100	100	100	100	100	100	100	100
2-parallel	50	50	50	50	50	50	50	50
3-parallel			33.3			33.3		
4-parallel		25		25		25		25
5-parallel					20			
6-parallel			16.7			16.7		
7-parallel							14.3	
8-parallel				12.5				12.5
10-parallel					10			
12-parallel						8.3		
14-parallel							7.15	
16-parallel								6.25

To use the table, it is merely necessary to determine the ratio of the numbers corresponding to the changed and original windings; the new winding voltage is then obtained if this ratio is multiplied by the original winding voltage. The following examples illustrate the procedure.

EXAMPLE 1. A 2,200-volt 3-phase 8-pole motor has a winding that is connected series-star. List all possible parallel-star connections and the corresponding voltages that must be used in each case.

Solution

2-parallel star: $50/100 \times 2{,}200 = 1{,}100$ volts
4-parallel star: $25/100 \times 2{,}200 = 550$ volts
8-parallel star: $12.5/100 \times 2{,}220 = 275$ volts

EXAMPLE 2. A 6-pole motor has a winding that is connected three-parallel delta, with a rating of 440 volts. How should this winding be reconnected for use on a 660-volt source?

Solution

The ratio of the new to the original voltage $= 660/440 = 1.5$
Per cent value for three-parallel (Table 2) $= 33.3$

Per cent value for new connection = 33.3 × 1.5 = 50
Connection for 50 per cent value (Table 2) = Two-parallel
Therefore, use a two-parallel delta connection

Star-delta Winding Transformations and Voltage Changes

For reasons that will appear later, it is frequently necessary or desirable to change a three-phase winding from a star connection to a delta connection, and vice versa. When this is done, the impressed emf across the motor must be changed if the voltage across each pole group is to remain the same as in the original design.

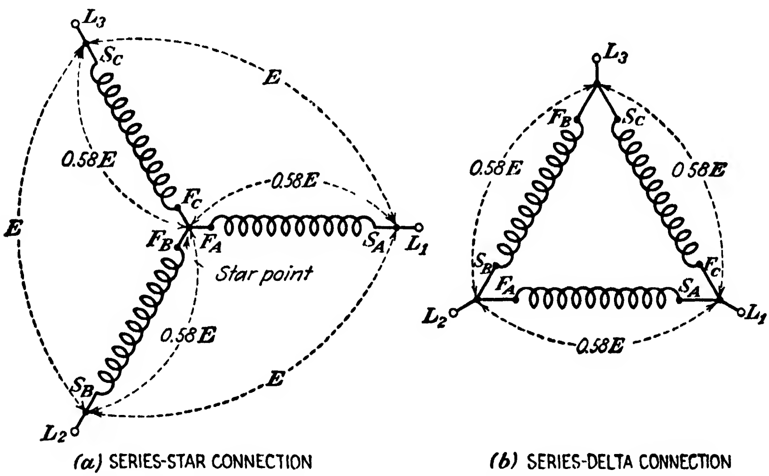


FIG. 106. Sketches showing relative voltages required for series-star and delta connections of the same winding.

Consider the simplified sketch of Fig. 106*a*, which represents a three-phase winding, connected series-star. Assuming E volts between line terminals S_A, S_B, and S_C, the voltage per phase will be $E/\sqrt{3}$, or $0.58E$. Now then, if this winding is reconnected series-delta, as in Fig. 106*b*, the line terminal voltage becomes the volts per phase. It follows, therefore, that the required emf for the series-delta winding is $0.58E$ because, under this condition, the volts per pole group remain unchanged.

The second principle concerning winding changes may now be stated as follows: *Whenever the winding connections are changed from a star to a delta of the same parallel grouping, the impressed emf must be lowered to 58 per cent of the original voltage; conversely, when the change is from delta to star of the same parallel grouping, the impressed emf must be raised to 173 per cent of the original voltage.*

EXAMPLE 3. A 440-volt induction motor winding is connected series-star. If the neutral point is opened and the three phases are interconnected in delta, what line voltage will produce the same operating performance as the series-star connection?

Solution

Line volts for delta = $0.58 \times 440 = 254$

Three-phase Winding Transformations and Voltage Changes

Combining the two principles concerning winding and voltage changes, a complete table may now be made, listing all possible star, delta, and parallel combinations of three-phase motor windings and their corresponding relative voltages as a percentage of the series-star connection. This is done in Table 3 for machines having 2 to 16 poles. As before, the table may be used by first determining the ratio of the numbers corresponding to the changed and original windings; the new winding voltage is then obtained if this ratio is multiplied by the original winding voltage. Two examples follow to illustrate the procedure.

TABLE 3. VOLTAGES OF RECONNECTED WINDINGS AS A PERCENTAGE OF SERIES-STAR WINDING

	2 Poles		4 Poles		6 Poles		8 Poles		10 Poles		12 Poles		14 Poles		16 Poles	
	Star	Delta	Star	Delta	Star	Delta	Star	Delta	Star	Delta	Star	Delta	Star	Delta	Star	Delta
Series	100	58	100	58	100	58	100	58	100	58	100	58	100	58	100	58
2-parallel	50	29	50	29	50	29	50	29	50	29	50	29	50	29	50	29
3-parallel					33.3	19.3					33.3	19.3				
4-parallel			25	14.5			25	14.5			25	14.5			25	14.5
5-parallel									20	11.6						
6-parallel					16.7	9.65					16.7	9.65				
7-parallel													14.3	8.28		
8-parallel							12.5	7.25							12.5	7.25
10-parallel									10	5.8						
12-parallel											8.35	4.83				
14-parallel													7.15	4.14		
16-parallel															6.25	3.63

EXAMPLE 4. A 550-volt 6-pole three-parallel star-connected winding is changed to a two-parallel delta. (*a*) What theoretically correct voltage should be used across the new connection? (*b*) What nearest standard voltage would prove satisfactory?

Solution

(*a*) The ratio of the new to the original voltage = 29/33.3 = 0.87. The new correct voltage should be 0.87 × 550 = 478

(*b*) The nearest standard voltage that would prove satisfactory is 460, which is about 4 per cent low. Since the output of a motor is approximately proportional to the *square* of the voltage, the motor could be expected to deliver about 92 per cent of its original rating at 460 volts

EXAMPLE 5. It is desired to change the winding connections of a 12-pole 440-volt series-delta motor so that it will operate satisfactorily from a 240-volt source. What change in winding connections should be made?

Solution

The ratio of the new to the original voltage = 240/440 = 0.546

Per cent value for series-delta (Table 3) = 58

Per cent value for new connection = 58 × 0.546 = 31.7

Connection nearest 31.7 per cent value (Table 3) = three parallel-star, which indicates a 33.3 per cent value

Therefore, use a three-parallel star, which is reasonably correct

Two-phase Winding Changes

Two-phase motor windings may also be changed so that they will perform satisfactorily on different voltages. Whether or not the two phases are interconnected is immaterial, however, since the voltage per phase is determined by considering the winding merely from the standpoint of paralleling pole groups. The same procedure followed in connection with three-phase windings, where Table 2 was used, is therefore applicable to two-phase windings.

The Star-delta Connections for Starting Induction Motors

An interesting application of the star-delta principle involves the starting of an induction motor at reduced voltage. As is well known, when full voltage is connected across this type of motor during the starting period, the current may be unusually high. To limit the current to values that are considered safe, it is, therefore, customary to reduce the motor-starting voltage by one of several methods; the starting current is directly proportional to the voltage across the winding phase. Now then, assuming that the motor operates normally when the winding is connected in delta, the starting voltage per winding phase will be only 58 per cent of normal if, during the starting period, a star connection is used. Thus the starting current will be reduced 42 per cent below the full-voltage starting condition.

Figure 107 illustrates the switching arrangement employed in this

starting scheme. To start the motor, the TPDT switch is closed in the "down" position; this connects the winding in star. After the motor reaches full speed, the switch is quickly closed in the "up" position; this connects the winding in delta, which is the normal operating connection.

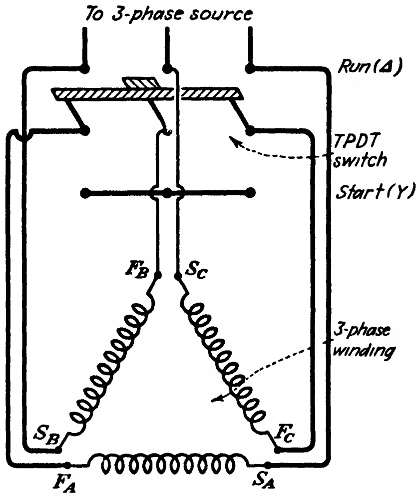


Fig. 107. Wiring connections for starting an induction motor by the star-delta method.

Summary

1. The number of turns in each phase of an a-c winding is determined by the operating voltage across that phase.

2. The volts per pole group in a winding is fixed by the original winding design, and must remain constant for any change in connections.

3. Whenever the voltage across a machine is changed, the winding connections must be changed so that the original volts per pole group remain unaltered.

4. Whenever the winding connections are changed, the impressed line voltage must be changed so that the original volts per pole group remain unaltered.

5. Any parallel-connected winding must always have the same number of series pole groups in each of the parallel paths.

6. Manufacturers frequently bring out nine leads from the winding of an induction motor so that it may be operated on either of two voltages, one twice the other. When this is done, the series-star connection is used for the higher potential and the two-parallel star for the half-voltage operation.

7. In all winding connections, it is imperative that standard current directions through the coils of the various pole groups be maintained.

8. Whenever the winding connections are changed from star to delta of the same parallel grouping, the impressed emf must be lowered to 58 per cent of the original voltage.

9. Whenever the winding connections are changed from delta to star of the same parallel grouping, the impressed emf must be raised to 173 per cent of the original voltage.

10. The same principles concerning parallel-winding and voltage changes are applicable to two-phase windings.

11. Three-phase motors are sometimes started by the so-called star-delta method, to limit the starting currents to reasonable values. This can be done only if the winding is designed to operate normally when connected in delta. Thus, when the winding is connected in star during the starting period, the impressed voltage per winding phase is reduced to 58 per cent of normal; the starting current is thereby reduced correspondingly.

CHAPTER 12

Fractional-pitch Lap Windings

Thus far, in the study of lap windings, all coils were assumed to have a span of exactly 180 electrical degrees; such windings are said to be *full-pitch.* Although full-pitch windings are employed in some designs, a more common winding arrangement is to have coils whose spans are less than 180 electrical degrees. Such windings, called *fractional-pitch,* have definite advantages over the full-pitch construction and are, therefore, the preferred type. They will be considered in this chapter.

Definition of Fractional Pitch

The term *pitch* refers to the span of a coil; in a double-layer lap winding it is the same for all the coils, since they are all exactly alike in size and shape. If the two sides of a coil are placed into slots that are 180 electrical degrees apart, both coil and winding are said to be *full-pitch.* For example, if a 4-pole winding were placed in a 48-slot core, it would be full-pitch if the coil-sides of each coil occupied slots 1 and 13, there being 48/4, or 12, slots per pole. Another term that is sometimes used to indicate a 180-degree pitch is *100 per cent pitch.*

When the coil span is less (and, in some special cases, more) than 180 electrical degrees, both coil and winding are referred to as *fractional-pitch.* Thus, if the foregoing 4-pole winding in the 48-slot core has coils that are placed in slots 1 and 12, or 1 and 11, or, in general, 1 and any number less than 13, both coils and winding are said to be *fractional-pitch.* The term *fractional pitch* derives from the fact that the coil span is a fraction of a pole pitch, *i.e.*, the distance between the centers of two adjacent poles, or 180 electrical degrees. Another designation for the fractional-pitch winding is on a percentage basis, which merely implies that the coil span is a certain per cent of a full-pitch (100 per cent) coil.

Again using the 48-slot core as an example, the following fractional pitches may be listed with their corresponding degrees and per cent values: Slots 1 to 12, 165 degrees, 91.7 per cent; slots 1 to 11, 150 degrees, 83.3 per cent; slots 1 to 10, 135 degrees, 75 per cent; slots 1 to 9, 120 degrees, 66.7 per cent; slots 1 to 8, 105 degrees, 58.3 per cent; slots 1 to 7, 90 degrees, 50 per cent. In practice, fractional-pitch windings are never less than 50

per cent and seldom less than 66.7 per cent. Figure 108 illustrates a number of fractional-pitch lap coils for windings with different slot, pole, and span combinations.

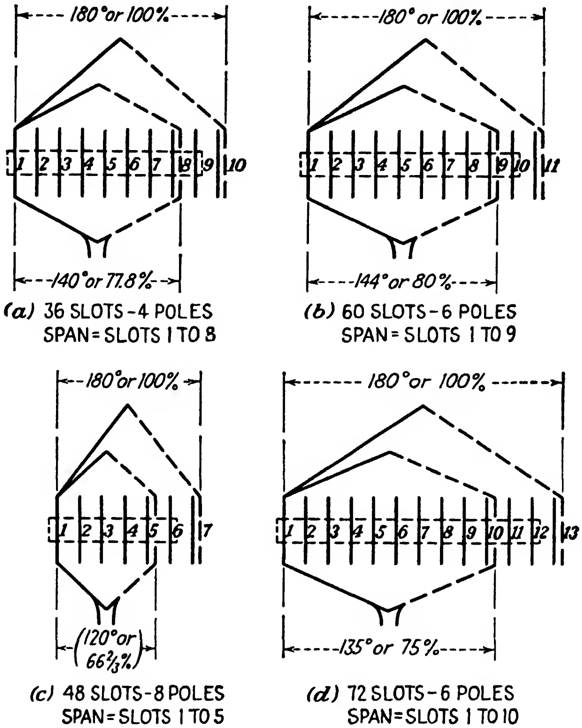


FIG. 108. Sketches illustrating fractional-pitch lap coils and their corresponding degrees and per cent values. The 100 per cent pitch coils are indicated for comparison.

Advantages of Fractional-pitch Windings

In alternators, it is extremely desirable that the generated alternating voltage wave be, as nearly as possible, a sine wave. Although the ideal is never attained in the practical machine, disturbances, in the form of harmonics, may be lessened by using fractional-pitch windings. Thus, for example, if a third harmonic interferes markedly with the generation of a sine wave (a third harmonic has a frequency that is three times the desired, or fundamental, frequency), a fractional pitch of 120 electrical degrees, *i.e.*, 66⅔ per cent, will entirely eliminate the particular harmonic. Or, if the fifth harmonic tends to distort the sine wave, a 144 degree (80 per cent) fractional-pitch winding will erase the disturbance. No single-coil pitch will eliminate all harmonics, but the one that is selected by the designer will usually help to develop a distortionless wave. In general,

however, a harmonic of the order n may be entirely eliminated if the per cent pitch is equal to $[1 - (1/n)] \times 100$.

Other factors remaining unchanged, the effect of a fractional pitch is to lower the generated voltage in the coils of an alternator, with a resulting reduced terminal emf. The practice is, therefore, equivalent to reducing the number of turns of wire in the coils of a full-pitch winding. Or, to put it another way, for the same terminal voltage, a fractional-pitch winding must have more turns per coil than a full-pitch winding. Advantage is taken of this fact, in winding design, by selecting a fractional pitch that in calculation yields a whole number of turns per coil, where a full-pitch winding would require part of a turn in addition to the complete turns. To illustrate, suppose calculations for a full-pitch winding indicate that $5\frac{1}{2}$ turns of wire should be used for each coil, under given operating conditions. Since partial turns are practically impossible, 6-turn fractional-pitch coils, with the correct coil span, will develop the same voltage as $5\frac{1}{2}$-turn full-pitch coils. Eq. 5 in Chap. 2 may be used to determine the correct fractional pitch in such cases. In the above example, $k_p = 5.5/6 = 0.917$. Since the sine of 66.5 degrees = 0.917, the coil pitch must be 2×66.5 degrees = 133 degrees. If the number of slots in the core does not permit the use of the calculated value, adjustments may usually be made in other quantities.

The average length of each turn of a fractional-pitch coil is less than that in the full-pitch coil because the end connections (the portions extending beyond the core at both ends) are shorter. This tends to reduce the winding resistance, and therefore, the copper loss, slightly, although the increased number of turns indicated above may offset the reduction somewhat. Much more important gains, however, are a stiffer winding, narrower (axially) bearing brackets, and consequently a shorter distance between bearings. Figure 108 clearly illustrates why the axial length of a fractional-pitch coil is less than that of a full-pitch coil; note the comparative difference between the overhangs of the two coils in each of the sketches. In other words, fractional-pitch windings tend to improve electrical machines mechanically.

The torque developed by an induction motor and the power factor at which it operates depend to a large extent upon flux, created by the stator winding, that does not link with the rotor conductors. This flux is called *leakage flux*, and it gives rise to the so-called *leakage reactance* of the motor. One way to improve the motor torque and power factor is to minimize the leakage flux, and therefore the leakage reactance; this may be accomplished to some extent by employing a fractional-pitch winding.

Still another advantage resulting from the shortening of the coil span is to reduce the magnetic noise developed in the motor. This is sometimes especially important in installations where quiet operation is essential.

Conductor Arrangements with Different Coil Spans

When a full-pitch polyphase double-layer lap winding is used, each slot contains conductors that are part of the *same* phase. This is clearly seen in Fig. 91, which illustrates a 36-slot 3-phase full-pitch lap winding. Note particularly that definite slots are allotted to each phase, with no slot con-

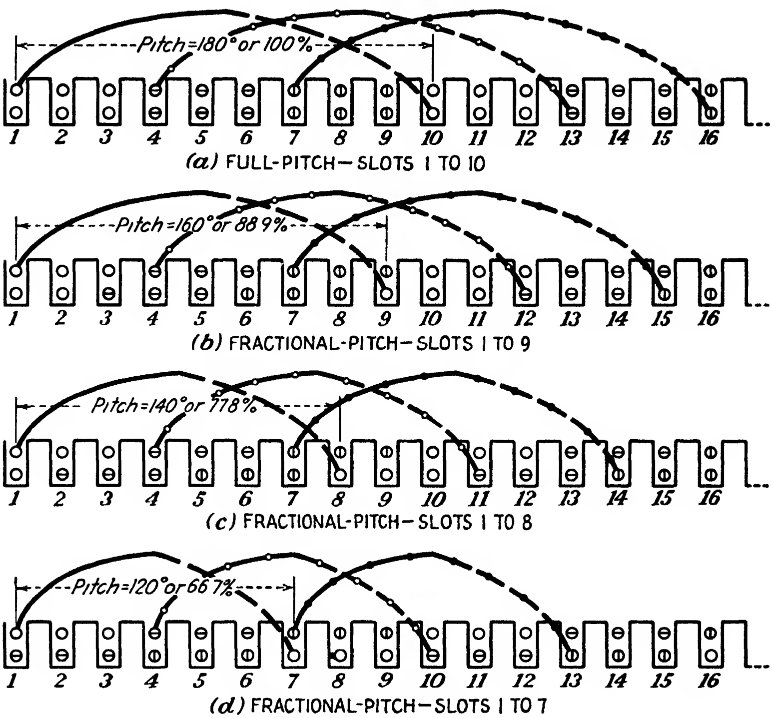


FIG. 109. Sketches illustrating arrangement of coil-sides in the slots of a 36-slot core for a 4-pole 3-phase double-layer lap winding with different coil pitches.

taining conductors that are parts of different phases. It is, in fact, as though three independent single-phase windings were placed in three separate portions of the core.

Fractional-pitch windings, on the other hand, differ from full-pitch windings in the above respect because the conductors in the various slots may or may not belong to the same phase. In two- and three-phase windings, no slot will have conductors that are parts of the same phase if the coil pitches are 90 and 120 electrical degrees, respectively. For all other fractional pitches, the top and bottom layer coil-sides will belong to different phases in some slots and the same phase in others.

Referring to Fig. 109, it will be observed that several arrangements of coil-sides are shown in a portion of a 36-slot core for a 4-pole 3-phase double-

layer winding. In the full-pitch winding (coil span = 1 to 10) every slot contains coil-sides that are part of the *same* phase, while in the 120-electrical degree fractional-pitch winding no slot has coil-sides that belong to the same phase. For the other two coil pitches, Figs. 109*b* and *c*, top and bottom coil-sides are phase matched in some slots and not in others.

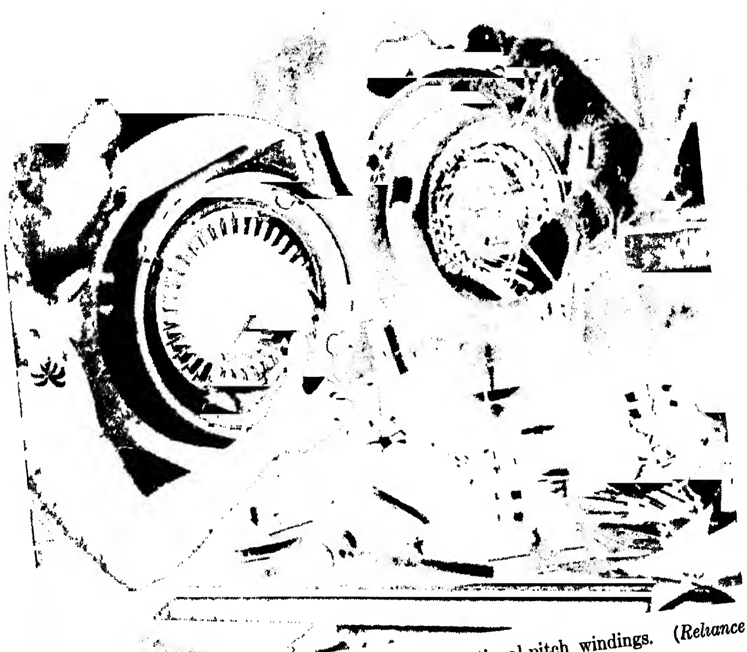


FIG. 110. Operators installing and connecting fractional-pitch windings. (*Reliance Electric and Engineering Co.*)

The important conclusion that must be drawn from the foregoing analysis is that a winding will create maximum flux for each ampere of current if the coil span is full-pitch, for coil pitches less than 100 per cent, the fluxes diminish on the basis of the pitch factor (see Chap. 2). Thus, in Figs. 109*b*, *c*, and *d*, where the fractional pitches are 160, 140, and 120 electrical degrees, respectively, and where the corresponding pitch factors are 0.985, 0.940, and 0.866, the total created fluxes will have values that are $0.985\phi_m$, $0.940\phi_m$, and $0.866\phi_m$, in the order given. Therefore, in so far as motors are concerned, where the developed torque is a direct function

of the flux, fractional-pitch windings usually have more turns of wire than full-pitch windings for equivalent output ratings.

Installing and Connecting Fractional-pitch Windings

The coils of all double-layer windings are inserted in the core in exactly the same way, regardless of whether the coil span is full-pitch or fractional-pitch. As was previously pointed out, in machines of comparatively small size it is the practice to form the coils in gangs (the number of coils per

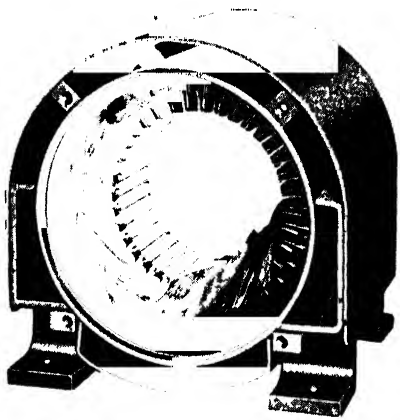


FIG. 111. Stator showing a fractional-pitch winding partially completed. See Fig. 110 for the starting operation. (*Reliance Electric and Engineering Co.*)

gang = slots/poles × phases), with the distance between coil-sides and the amount of overhang determined by the core dimensions and the coil span. Moreover, winding connections for full-pitch and fractional-pitch coils are identical, so that what has been said concerning the former applies equally well to the latter.

Figure 110 shows an operator (in the foreground) starting a 4-pole 3-phase fractional-pitch lap winding in a 36-slot core. Note the three-coil gangs and the various kinds of insulation on the table; also observe that the left coil-sides of the first pole group are in place in the slots. Since the coil span is slots 1 to 8, this is a fractional-pitch winding with a 140-degree, or 77.8 per cent, pitch; it is represented by Fig. 109*c*. As the winding installation proceeds, phase insulation must be placed in the end connections between the coils of successive pole groups. This may be seen in Fig. 111, which is the same stator, illustrated by Fig. 110, after one-half of the coils were installed. Particular attention is called to the right coil-sides of the first seven coils that are deliberately left out of the slots. Since these coil-sides must occupy the upper layer, they cannot be inserted into

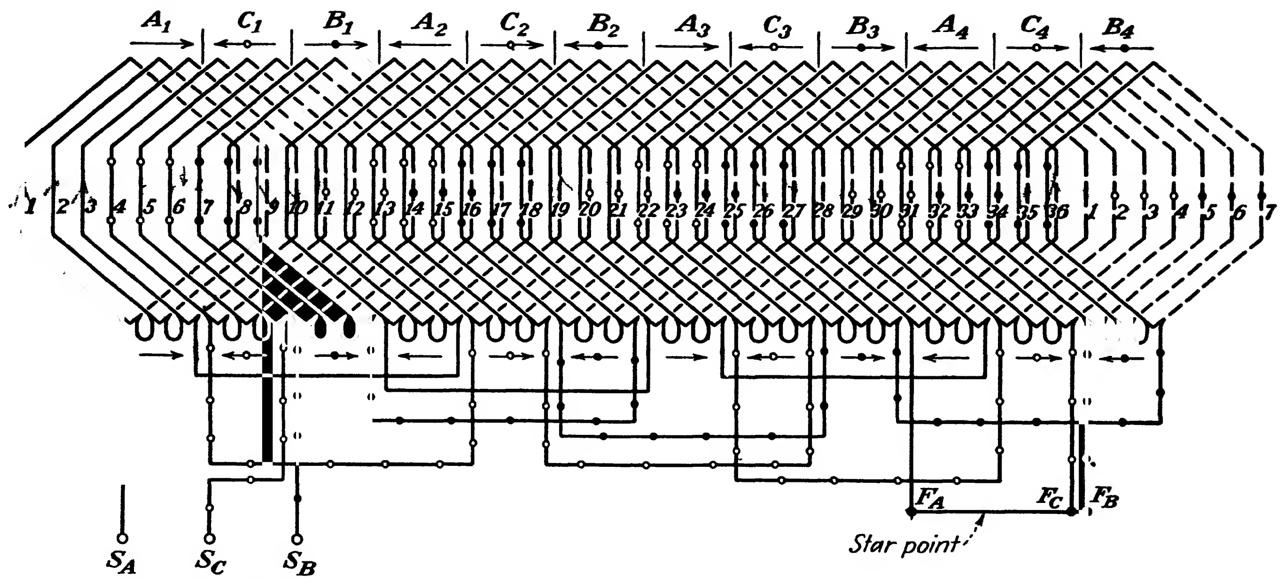


FIG. 112. Complete wiring diagram of a 4-pole 3-phase fractional-pitch star-connected lap winding in a 36-slot core. The coil pitch is slots 1 to 8; this is 140 electrical degrees, or 77.8 per cent. See Figs. 109*c*, 110, and 111 for simplified sketch and photographs of this winding.

FIG. 113. Stator core with 48 slots shown with one two-coil gang in the slots. See Fig. 114 for the complete wiring diagram for this fractional-pitch winding. (*Reliance Electric and Engineering Co.*)

their proper slots until the left coil-sides of the last seven coils have been placed in the lower layer. Then, after all the coils are in place, the final interconnections are made between pole groups and phases; this operation may be seen in the background of Fig. 110.

To emphasize further the importance of the typical fractional-pitch winding represented by Figs. 109*c*, 110, and 111, a complete diagram of connections is given in Fig. 112. Especially notice that only one-third of all the slots, 12 in number, contain top and bottom coil-sides that belong to the same phase; these are slots 1, 10, 19, and 28 for phase *A*, slots 4, 13, 22, and 31 for phase *C*, and slots 7, 16, 25, and 34 for phase *B*.

A photograph illustrating the start of another fractional-pitch lap

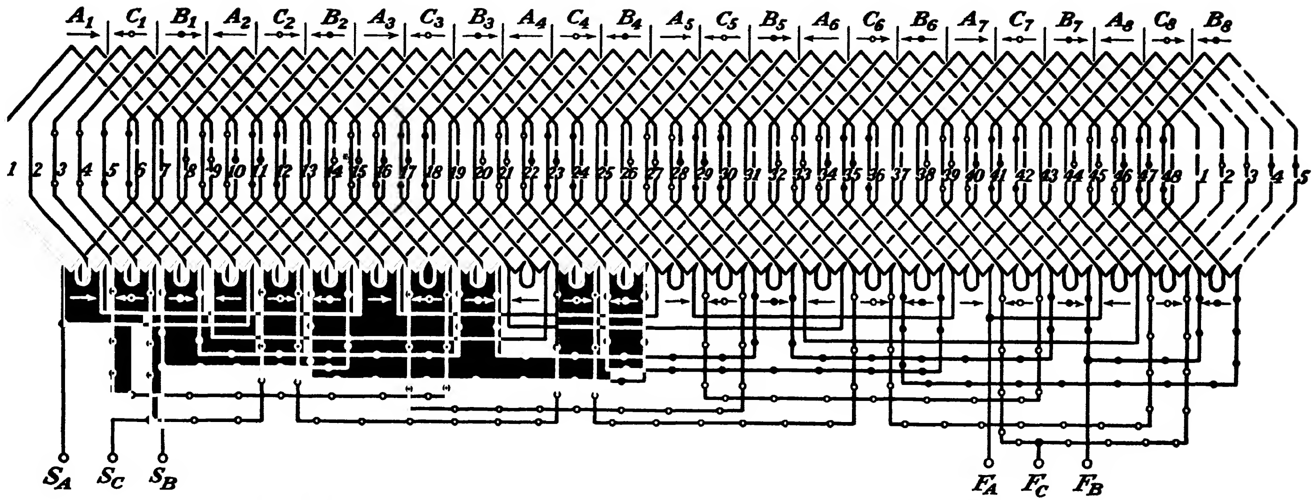


FIG. 114. Complete wiring diagram of an 8-pole 3-phase fractional-pitch two-parallel lap winding in a 48-slot core. The coil pitch is slots 1 to 6; this is 150 electrical degrees or 83.3 per cent. Six terminal leads are brought out so that the winding may be connected in star or delta. See Fig. 113 for a photograph of the start of this winding.

winding is shown in Fig. 113. It is for eight poles and three phases, with a coil span of slots 1 to 6, in a 48-slot core. One of the two-coil gangs ($48/8 \times 3$) may be seen in the lower left, as well as another with the left coil-sides in the slots. Since there are six slots per pole (48/8) in this winding, the fractional-pitch is $5/6 \times 180$ degrees = 150 degrees or $5/6 \times 100 = 83\frac{1}{3}$ per cent. The complete wiring diagram is represented by Fig. 114, in which six terminal leads are brought out for either a star or delta connection. Note particularly that only one-half of all the slots, 24 in number, contain top and bottom coil-sides that are part of the same phase.

Summary

1. The pitch of a coil refers to its span. In double-layer lap windings all coils have the same pitch.

2. If the span of a coil is 180 electrical degrees, it is said to be full-pitch; the winding is then called a full-pitch winding.

3. If the span of a coil is less than 180 electrical degrees, it is said to be fractional-pitch; the winding is then called a fractional-pitch winding.

4. The pitch of a coil or winding is often specified in per cent. A 180-electrical degree pitch is equivalent to 100 per cent, while a pitch less than 180 degrees is the proportional part of 100 per cent.

5. Fractional-pitch windings have the following advantages: (1) The voltage wave of an alternator may be made to approach the ideal sine wave; (2) the amount of copper is reduced; (3) the copper loss is reduced; (4) adjustments may be made in the number of turns per coil so that fractional turns may be avoided; (5) the coil extensions are shorter, which results in a stiffer winding, narrower bearing brackets, and a shorter distance between bearings; (6) the leakage reactance is reduced, and this results in more torque and better power factor in a motor; (7) magnetic noise may be reduced for quiet operation.

6. In full-pitch windings, each slot contains conductors that are part of the *same* phase.

7. In two-phase windings, no slot will contain conductors that belong to the same phase if the pitch is 90 electrical degrees.

8. In three-phase windings, no slot will contain conductors that belong to the same phase if the pitch is 120 electrical degrees.

9. For all pitches other than those listed in items 7 and 8, top and bottom layer coil-sides will belong to different phases in some slots, and the same phase in other slots.

10. A fractional-pitch winding creates less flux per ampere than an equivalent full-pitch winding.

11. Windings are installed in a core in exactly the same way, regardless of whether the coil span is full-pitch or fractional-pitch.

CHAPTER 13

Fractional-slot Lap Windings

The number of slots in the core of a machine in which a double-layer lap winding is placed is generally a multiple of the product of poles and phases. Under this condition all pole groups have exactly the same number of coils, connected in series, of course; the coils per pole group will then be (*slots/poles × phases*), because total slots equal total coils. In some winding designs, however, (*slots/poles × phases*) does not yield an integer, and this obviously means that all pole groups will *not* have the same number of coils. Although windings of this sort are not perfectly symmetrical, machine operation will be satisfactory if the unequal pole groups are distributed around the core in a fairly uniform manner. This chapter will be concerned with the problem of arranging the pole groups in a way that will provide a good degree of symmetry.

Coils per Pole Group in Symmetrical Lap Windings

All polyphase double-layer lap windings, whether symmetrical or unsymmetrical, must have the same number of coils per phase. This does not mean that all pole groups must have equal numbers of coils, although complete symmetry will result when they do. If a core has a number of slots that is equal to the product of an *integer* and poles × phases (1) all pole groups will be identical, (2) the winding will be symmetrical, and (3) the integer represents the number of coils in each pole group. Table 4 lists all the possible coils-per-pole-group combinations for 2- to 32-pole 3-phase symmetrical windings, in cores having 12 to 96 slots.

It is interesting to note in the table that symmetrical three-phase windings can result only if the number of slots (or coils) is a multiple of six. Moreover, the integers that appear under each of the pole headings are obtained by dividing the number of slots by $3 \times P$. For example, a 72-slot core can be wound symmetrically for 2, 4, 6, 8, 12, and 24 poles; and the number of coils per pole group will be, respectively, $72/3 \times 2 = 12$, $72/3 \times 4 = 6$, $72/3 \times 6 = 4$, $72/3 \times 8 = 3$, $72/3 \times 12 = 2$, and $72/3 \times 24 = 1$.

Table 5 lists all the possible coils-per-pole-group combinations for 2- to 32-pole 2-phase symmetrical windings, in cores having 12 to 64 slots.

TABLE 4. COILS PER POLE GROUP IN SYMMETRICAL THREE-PHASE LAP WINDINGS

Slots or coils	Coils per pole group for															
	$P=2$	$P=4$	$P=6$	$P=8$	$P=10$	$P=12$	$P=14$	$P=16$	$P=18$	$P=20$	$P=22$	$P=24$	$P=26$	$P=28$	$P=30$	$P=32$
12	2	1														
18	3		1													
24	4	2		1												
30	5				1											
36	6	3	2			1										
42	7						1									
48	8	4		2				1								
54	9		3						1							
60	10	5			2					1						
66	11										1					
72	12	6	4	3		2						1				
78	13												1			
84	14	7					2							1		
90	15		5		3										1	
96	16	8		4				2								1

TABLE 5. COILS PER POLE GROUP IN SYMMETRICAL TWO-PHASE LAP WINDINGS

Slots or coils	Coils per pole group for															
	$P=2$	$P=4$	$P=6$	$P=8$	$P=10$	$P=12$	$P=14$	$P=16$	$P=18$	$P=20$	$P=22$	$P=24$	$P=26$	$P=28$	$P=30$	$P=32$
12	3		1													
16	4	2		1												
20	5				1											
24	6	3	2			1										
28	7						1									
32	8	4		2				1								
36	9		3						1							
40	10	5			2					1						
44	11										1					
48	12	6	4	3		2						1				
52	13												1			
56	14	7					2							1		
60	15		5		3										1	
64	16	8		4				2								1

Referring to the table, observe that symmetrical two-phase windings can result only if the number of slots (or coils) is a multiple of four. Moreover, the integers that appear under each of the pole headings are obtained by dividing the number of slots by $2 \times P$. For example, a 48-slot core can be wound symmetrically for 2, 4, 6, 8, 12, and 24 poles, and the number of coils per pole group will be, respectively, $48/2 \times 2 = 12$, $48/2 \times 4 = 6$, $48/2 \times 6 = 4$, $48/2 \times 8 = 3$, $48/2 \times 12 = 2$, and $48/2 \times 24 = 1$.

Determining Coils per Pole Group in Unsymmetrical Lap Windings

1. *Three-phase windings.* The first important requirement for all polyphase windings is that there be the same number of coils in every phase. Assuming all pole groups to be connected in series, the total number of coils in a three-phase lap winding must, therefore, be a multiple of three; this implies that the number of core slots must be a multiple of three. Now then, if the number of poles divides evenly into coils per phase, the winding will be symmetrical; if not, the winding will be unsymmetrical in the sense that all pole groups will not be similar. Under the latter condition one or more of the P pole groups will have one more coil than the others.

An example should make this clear. A 48-slot core can be used for three-phase service because 48 is a multiple of 3; each phase will have 16 coils. Since 16 divides evenly by 2, 4, 8, and 16, symmetrical lap windings will result if they are for two, four, eight, or sixteen poles; under these conditions the number of coils per pole group will be 8, 4, 2, and 1, respectively. If the winding is for six poles, however, the *average* number of coils per pole group will be $16/6 = 2\frac{2}{3}$. Since fractional coils are obviously impossible, a practical winding must, therefore, have two pole groups of two coils each and four pole groups of three coils each. Note that these combinations result in a total of six pole groups and a total of sixteen coils for each phase, as required.

Another example is a 144-slot core with a 14-pole 3-phase lap winding. Since 144 is a multiple of three, there will be 48 coils per phase. With 14 poles, the average number of coils per pole group will be $48/14 = 3\frac{3}{7}$. Again, since fractional coils are impossible, a combination of pole groups must be found that fulfills the following requirements for each phase: (1) There must be 14 pole groups; (2) there must be a total of 48 coils; (3) coils per pole group must not differ by more than one coil in the various groups if the unbalance is to be a minimum. After a little thought on the matter—since no general rule can be given for this—it is found that the only combination that will satisfy the foregoing is 6 pole groups of 4 coils and 8 pole groups of 3 coils. Note that $(6 \times 4) + (8 \times 3) = 48$ coils, and $(6 + 8) = 14$ pole groups.

Exactly how the pole groups with the differing numbers of coils are arranged for all three phases will be discussed later; for the present it is well to understand that satisfactory operation will result if the unequal pole groups are distributed fairly evenly.

Table 6 lists cores having 15 to 99 slots, with possible three-phase windings having 2 to 32 poles. Under each pole heading is given the number of unsymmetrical *groups G* and the number of *coils per pole group C/G* for the various slot or coil combinations. Thus, a 69-slot machine wound for 10 poles will have, per phase, 7 groups of 2 coils and 3 groups of 3 coils; total groups = $(7 + 3) = 10$, and total coils = $(7 \times 2) + (3 \times 3) = 23$. Also, a 93-coil 12-pole winding will have, per phase, 5 groups of 2 coils and 7 groups of 3 coils; total groups = $(5 + 7) = 12$, and total coils = $(5 \times 2) + (7 \times 3) = 31$.

2. *Two-phase windings.* Table 7 lists cores having 12 to 66 slots, with possible two-phase windings having 2 to 32 poles. It is used in exactly the same way as is the three-phase table. For example, a 54-coil 8-pole winding will require, per phase, 5 groups of 3 coils and 3 groups of 4 coils; total groups = $(5 + 3) = 8$, and total coils = $(5 \times 3) + (3 \times 4) = 27$.

Systematic Arrangement of Unsymmetrical Three-phase Windings —Special Rules

Unsymmetrical windings always have two differing sets of pole groups per phase; there is one more coil in each pole group of one set than in each pole group of the other set.

Rule 1. When there are exactly the same number of pole groups in each of the two sets, the three-phase winding must be arranged so that successive pole groups have different numbers of coils. This rule leads to an extremely simple way of arranging the pole groups, because the sequence is systematic and regular. To lay out such a winding, the following procedure is suggested: (1) Calculate the number of coils per phase by dividing the slots by 3; (2) determine the number of each set of pole groups with the corresponding coils per pole group, using Table 6 or working out the proper combinations by trial and error; (3) draw a circle, divide it first into P parts, and then divide each pole section into three parts to represent pole groups; (4) label each pole group with proper phase letter A, B, or C; (5) starting at any point, place numbers in each pole-group division in regular succession around the circle, alternating the numbers corresponding to the two different coils-per-pole-group values found in (2).

Two examples will now be given to illustrate the procedure.

TABLE 6. GROUPS AND COILS PER POLE GROUP IN UNSYMMETRICAL THREE-PHASE LAP WINDINGS

Slots or coils	Coils per phase	Groups (G) and coils per pole group (C/G) for																													
		$P = 2$		$P = 4$		$P = 6$		$P = 8$		$P = 10$		$P = 12$		$P = 14$		$P = 16$		$P = 18$		$P = 20$		$P = 22$		$P = 24$		$P = 26$		$P = 28$		$P = 30$		$P = 32$	
		G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G	G	C/G
15	5	1 1	2 3	3 1	1 2																												
18	6	S		2 2	1 2	S																											
21	7	1 1	3 4	1 3	1 2	5 1	1 2																										
24	8	S		S		4 2	1 2	S																									
27	9	1 1	4 5	3 1	2 3	3 3	1 2	7 1	1 2																								
30	10	S		2 2	2 3	2 4	1 2	6 2	1 2	S																							
33	11	1 1	5 6	1 3	2 3	1 5	1 2	5 3	1 2	9 1	1 2																						
36	12	S		S		S		4 4	1 2	8 2	1 2	S																					
39	13	1 1	6 7	3 1	3 4	5 1	2 3	3 5	1 2	7 3	1 2	11 1	1 2																				
42	14	S		2 2	3 4	4 2	2 3	2 6	1 2	6 4	1 2	10 2	1 2	S																			
45	15	1 1	7 8	1 3	3 4	3 3	2 3	1 7	1 2	5 5	1 2	9 3	1 2	13 1	1 2																		
48	16	S		S		2 4	2 3	S		4 6	1 2	8 4	1 2	12 2	1 2	S																	
51	17	1 1	8 9	3 1	4 5	1 5	2 3	7 1	2 3	3 7	1 2	7 5	1 2	11 3	1 2	15 1	1 2																
54	18	S		2 2	4 5	S		6 2	2 3	2 8	1 2	6 6	1 2	10 4	1 2	14 2	1 2	S															
57	19	1 1	9 10	1 3	4 5	5 1	3 4	5 3	2 3	1 9	1 2	5 7	1 2	9 5	1 2	13 3	1 2	17 1	1 2														

60	20	S	S	4 3 2 4	4 2 4 3	S	4 1 8 2	8 1 6 2	12 1 4 2	16 1 2 2	S						
63	21	1 10 1 11	3 5 1 6	3 3 3 4	3 2 5 3	9 2 1 3	3 1 9 2	7 1 7 2	11 1 5 2	15 1 3 2	19 1 1 2						
66	22	S	2 5 2 6	2 3 4 4	2 2 6 3	8 2 2 3	2 1 10 2	6 1 8 2	10 1 6 2	14 1 4 2	18 1 2 2	S					
69	23	1 11 1 12	1 5 3 6	1 3 5 4	1 2 7 3	7 2 3 3	1 1 11 2	5 1 9 2	9 1 7 2	13 1 5 2	17 1 3 2	21 1 1 2					
72	24	S	S	S	S	6 2 4 3	S	4 1 10 2	8 1 8 2	12 1 6 2	16 1 4 2	20 1 2 2	S				
75	25	1 12 1 13	3 6 1 7	5 4 1 5	7 3 1 4	5 2 5 3	11 2 1 3	3 1 11 2	7 1 9 2	11 1 7 2	15 1 5 2	19 1 3 2	23 1 1 2				
78	26	S	2 6 2 7	4 4 2 5	6 3 2 4	4 2 6 3	10 2 2 3	2 1 12 2	6 1 10 2	10 1 8 2	14 1 6 2	18 1 4 2	22 1 2 2	S			
81	27	1 13 1 14	1 6 3 7	3 4 3 5	5 3 3 4	3 2 7 3	9 2 3 3	1 1 13 2	5 1 11 2	9 1 9 2	13 1 7 2	17 1 5 2	21 1 3 2	25 1 1 2			
84	28	S	S	2 4 4 5	4 3 4 4	2 2 8 3	8 2 4 3	S	4 1 12 2	8 1 10 2	12 1 8 2	16 1 6 2	20 1 4 2	24 1 2 2	S		
87	29	1 14 1 15	3 7 1 8	1 4 5 5	3 3 5 4	1 2 9 3	7 2 5 3	13 2 1 3	3 1 13 2	7 1 11 2	11 1 9 2	15 1 7 2	19 1 5 2	23 1 3 2	27 1 1 2		
90	30	S	2 7 2 8	S	2 3 6 4	S	6 2 6 3	12 2 2 3	2 1 14 2	6 1 12 2	10 1 10 2	14 1 8 2	18 1 6 2	22 1 4 2	26 1 2 2	S	
93	31	1 15 1 16	1 7 3 8	5 5 1 6	1 3 7 4	9 3 1 4	5 2 7 3	11 2 3 3	1 1 15 2	5 1 13 2	9 1 11 2	13 1 9 2	17 1 7 2	21 1 5 2	25 1 3 2	29 1 1 2	
96	32	S	S	4 5 2 6	S	8 3 2 4	4 2 8 3	10 2 4 3	S	4 1 14 2	8 1 12 2	12 1 10 2	16 1 8 2	20 1 6 2	24 1 4 2	28 1 2 2	S
99	33	1 16 1 17	3 8 1 9	3 5 3 6	7 4 1 5	7 3 3 4	3 2 9 3	9 2 5 3	15 2 1 3	3 1 15 2	7 1 13 2	11 1 11 2	15 1 9 2	19 1 7 2	23 1 5 2	27 1 3 2	31 1 1 2

S = Symmetrical winding (see Table 4); *G* = No. of pole groups per phase; *C/G* = No. of coils per pole group

TABLE 7 GROUPS AND COILS PER POLE GROUP IN UNSYMMETRICAL TWO-PHASE LAP WINDINGS

Slots or coils	Coils per phase	Groups (G) and coils per pole groups (C G) for																													
		P = 2		P = 4		P = 6		P = 8		P = 10		P = 12		P = 14		P = 16		P = 18		P = 20		P = 22		P = 24		P = 26		P = 28		P = 30		P = 32	
		G	C/G	G	C/G	G	C/G	G	C/G	G	C G	G	C G	G	C G	G	C G	G	C/G	G	C G	G	C G	G	C G	G	C G	G	C G	G	C G	G	C/G
12	6	S		2 2	1 2	S																											
14	7	1 1	3 4	1 3	1 2	5 1	1 2																										
16	8	S		S		4 2	1 2	S																									
18	9	1 1	4 5	3 1	2 3	3 3	1 2	7 1	1 2																								
20	10	S		2 2	2 3	2 4	1 2	6 2	1 2	S																							
22	11	1 1	5 6	1 3	2 3	1 5	1 2	5 3	1 2	9 1	1 2																						
24	12	S		S		S		4 4	1 2	8 2	1 2	S																					
26	13	1 1	6 7	3 1	3 4	5 1	2 3	3 5	1 2	7 3	1 2	11 1	1 2																				
28	14	S		2 2	3 4	4 2	2 3	2 6	1 2	6 4	1 2	10 2	1 2	S																			
30	15	1 1	7 8	1 3	3 4	3 3	2 3	1 7	1 2	5 5	1 2	9 3	1 2	13 1	1 2																		
32	16	S		S		2 4	2 3	S		4 6	1 2	8 4	1 2	12 2	1 2	S																	
34	17	1 1	8 9	3 1	4 5	1 5	2 3	7 1	2 3	3 7	1 2	7 5	1 2	11 3	1 2	15 1	1 2																
36	18	S		2 2	4 5	S		6 2	2 3	2 8	1 2	6 6	1 2	10 4	1 2	14 2	1 2	S															
38	19	1 1	9 10	1 3	4 5	5 1	3 4	5 3	2 3	1 9	1 2	5 7	1 2	9 5	1 2	13 3	1 2	17 1	1 2														
40	20	S		S		4 2	3 4	4 4	2 3	S		4 8	1 2	8 6	1 2	12 4	1 2	16 2	1 2	S													

42	21	1 10 1 11	3 5 1 6	3 3 3 4	3 2 5 3	9 2 1 3	3 1 9 2	7 1 7 2	11 1 5 2	15 1 3 2	19 1 1 2						
44	22	*S*	2 5 2 6	2 3 4 4	2 2 6 3	8 2 2 3	2 1 10 2	6 1 8 2	10 1 6 2	14 1 4 2	18 1 2 2	*S*					
46	23	1 11 1 12	1 5 3 6	1 3 5 4	1 2 7 3	7 2 3 3	1 1 11 2	5 1 9 2	9 1 7 2	13 1 5 2	17 1 3 2	21 1 1 2					
48	24	*S*	*S*	*S*	*S*	6 2 4 3	*S*	4 1 10 2	8 1 8 2	12 1 6 2	16 1 4 2	20 1 2 2	*S*				
50	25	1 12 1 13	3 6 1 7	5 4 1 5	7 3 1 4	5 2 5 3	11 2 1 3	3 1 11 2	7 1 9 2	11 1 7 2	15 1 5 2	19 1 3 2	23 1 1 2				
52	26	*S*	2 6 2 7	4 4 2 5	6 3 2 4	4 2 6 3	10 2 2 3	2 1 12 2	6 1 10 2	10 1 8 2	14 1 6 2	18 1 4 2	22 1 2 2	*S*			
54	27	1 13 1 14	1 6 3 7	3 4 3 5	5 3 3 4	3 2 7 3	9 2 3 3	1 1 13 2	5 1 11 2	9 1 9 2	13 1 7 2	17 1 5 2	21 1 3 2	25 1 1 2			
56	28	*S*	*S*	2 4 4 5	4 3 4 4	2 2 8 3	8 2 4 3	*S*	4 1 12 2	8 1 10 2	12 1 8 2	16 1 6 2	20 1 4 2	24 1 2 2	*S*		
58	29	1 14 1 15	3 7 1 8	1 4 5 5	3 3 5 4	1 2 9 3	7 2 5 3	13 2 1 3	3 1 13 2	7 1 11 2	11 1 9 2	15 1 7 2	19 1 5 2	23 1 3 2	27 1 1 2		
60	30	*S*	2 7 2 8	*S*	2 3 6 4	*S*	6 2 6 3	12 2 2 3	2 1 14 2	6 1 12 2	10 1 10 2	14 1 8 2	18 1 6 2	22 1 4 2	26 1 2 2	*S*	
62	31	1 15 1 16	1 7 3 8	5 5 1 6	1 3 7 4	9 3 1 5	5 2 7 3	11 2 3 3	1 1 15 2	5 1 13 2	9 1 11 2	13 1 9 2	17 1 7 2	21 1 5 2	25 1 3 2	29 1 1 2	
64	32	*S*	*S*	4 5 2 6	*S*	8 3 2 4	4 2 8 3	10 2 4 3	*S*	4 1 14 2	8 1 12 2	12 1 10 2	16 1 8 2	20 1 6 2	24 1 4 2	28 1 2 2	*S*
66	33	1 16 1 17	3 8 1 8	3 5 3 6	7 4 1 5	7 3 3 4	3 2 9 3	9 2 5 3	15 2 1 3	3 1 15 2	7 1 13 2	11 1 11 2	15 1 9 2	19 1 7 2	23 1 5 2	27 1 3 2	31 1 1 2

S = Symmetrical winding (see Table 5); G = No. of pole groups per phase; C/G = No. of coils per pole group.

EXAMPLE 1. Lay out the coils for a six-pole lap winding in a 63-slot core, and connect the pole groups and phases in series-delta.

Solution

(*a*) Coils per phase = 63/3 = 21

(*b*) Referring to Table 6, there will be 3 pole groups of 3 coils each, and 3 pole groups of 4 coils each. Total pole groups per phase = (3 + 3) = 6; total coils per phase = (3 × 3) + (3 × 4) = 21

(*c*) Figure 115*a* shows a circle divided into a total of 18 pole group parts, with phase letters properly identifying each part

(*d*) Figure 115*b* shows the simple numbering scheme indicating the number of coils in each pole group. Note that the numbers 3 and 4 follow each other around the circle with complete regularity, thus: 3, 4, 3, 4, 3, etc.

(*e*) Figure 115*c* shows the winding connected in series-delta

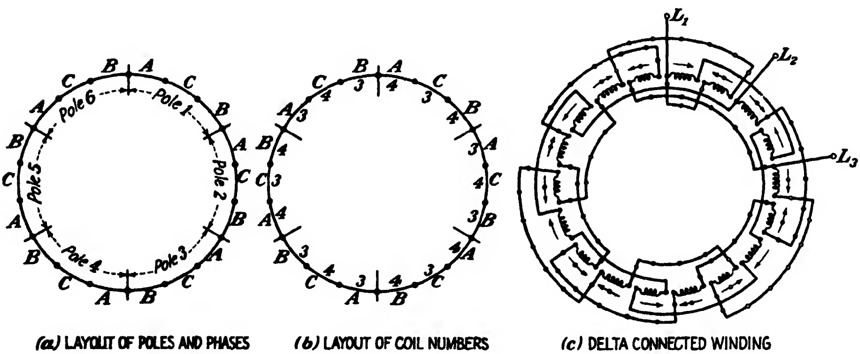


FIG. 115. Steps in the layout and connection of a 6-pole 3-phase unsymmetrical lap winding for a 63-slot core. This winding is connected series-delta. (See Example 1.)

EXAMPLE 2. Lay out the coils for a ten-pole lap winding in a 135-slot core, and connect the pole groups and phases in series-star.

Solution

(*a*) Coils per phase = 135/3 = 45

(*b*) Determined by trial and error, this winding must have 5 pole groups of 4 coils each, and 5 pole groups of 5 coils each. Total pole groups per phase = (5 + 5) = 10; total coils per phase = (5 × 4) + (5 × 5) = 45

(*c*) Figure 116 shows the schematic diagram of the winding with the phase letters and the corresponding coil numbers (4 and 5) on the pole groups. Note the regular sequence of numbers 4, 5, 4, 5, 4, etc.

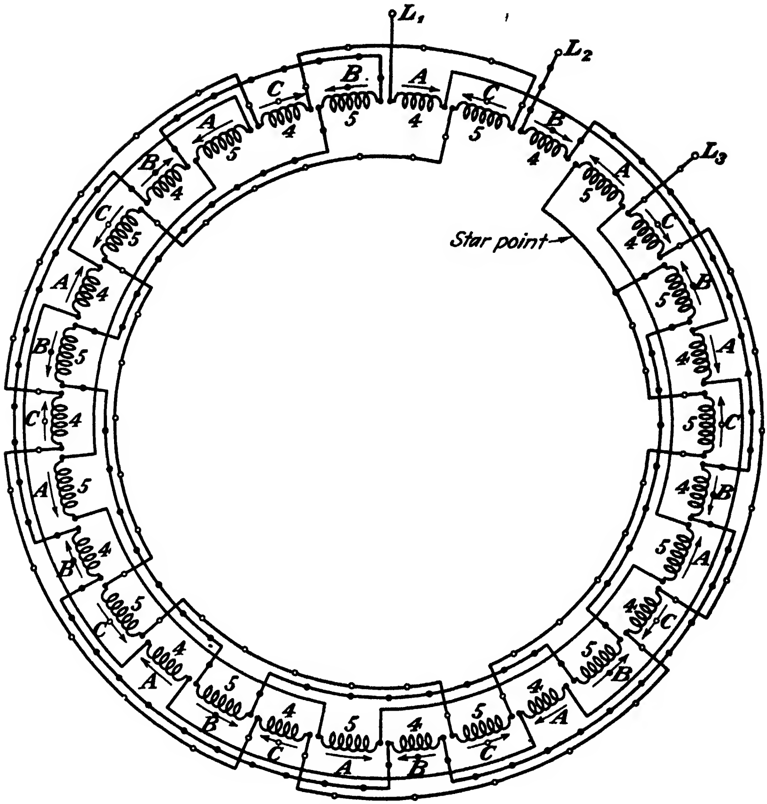


FIG. 116. Schematic diagram of an unsymmetrical 10-pole 3-phase lap winding for a 135-slot core showing the phase letters and the corresponding coil numbers on the pole groups. This winding is connected series-star. (See Example 2.)

Rule 2. When there are three times as many pole groups in one set, *X*, as in the other set, *Y*, the three-phase winding must be arranged so that the pole groups follow the regular sequence, *X–X–X–Y*, *X–X–X–Y*, *X–X–X–Y*, etc.

This rule is illustrated by two examples with their accompanying winding diagrams.

EXAMPLE 3. Lay out the coils for an eight-pole lap winding in a 90-slot core, and connect the pole groups and phases in two-parallel star.

Solution

(*a*) Coils per phase = 90/3 = 30

(*b*) Referring to Table 6, there will be 2 pole groups of 3 coils each, and

6 pole groups of 4 coils each. Total pole groups per phase = (2 + 6) = 8; total coils per phase = (2 × 3) + (6 × 4) = 30

(*c*) Figure 117 shows the schematic diagram of the winding with the phase letters and the corresponding coil numbers (3 and 4) on the pole groups. Note the regular sequence of numbers 4–4–4–3, 4–4–4–3, 4–4–4–3, etc. It should be pointed out that an unsymmetrical winding may be connected with parallel paths in each phase—two-parallel in this example—only when all parallel paths have equal numbers of coils

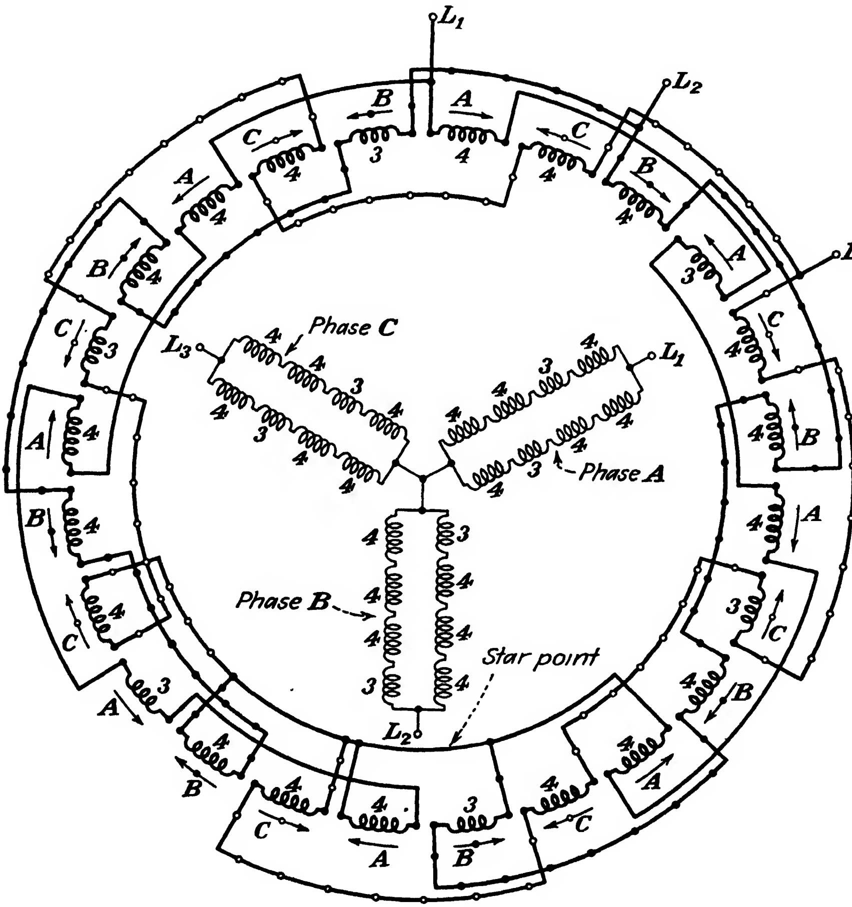


FIG. 117. Schematic diagram of an unsymmetrical 8-pole 3-phase lap winding for a 90-slot core showing the phase letters and the corresponding coil numbers on the pole groups. This winding is connected two-parallel star. (See Example 3.)

EXAMPLE 4. Lay out the coils for a 12-pole lap winding in a 117-slot core, and connect the pole groups and phases in three-parallel star.

Solution

(*a*) Coils per phase = 117/3 = 39

(*b*) Determined by trial and error, this winding must have 3 pole groups of 4 coils each, and 9 pole groups of 3 coils each. Total pole groups per phase = (3 + 9) = 12; total coils per phase = (3 × 4) + (9 × 3) = 39

(*c*) Figure 118 shows the schematic diagram of the winding, with the phase letters and the corresponding coil numbers (4 and 3) on the pole groups. Note the regular sequence of the numbers 3-3-3-4, 3-3-3-4, 3-3-3-4, etc. In this three-parallel winding, each of the paths in each phase has 13 coils

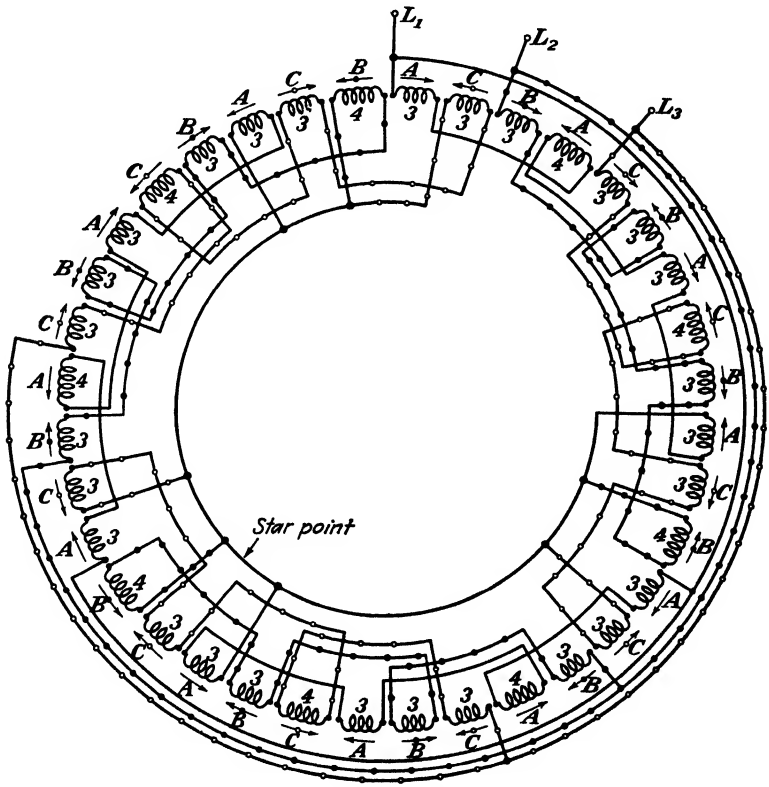


FIG. 118. Schematic diagram of an unsymmetrical 12-pole 3-phase lap winding for a 117-slot core showing the phase letters and the corresponding coil numbers on the pole groups. This winding is connected three-parallel star. (See Example 4.)

Systematic Arrangement of Unsymmetrical Two-phase Windings —Special Rules

Rule 3. When there are exactly the same number of pole groups in each of the two sets, the two-phase winding must be arranged

so that pairs of the two different numbers of coils per pole group follow in succession around the core.

This simple rule is illustrated by the following example and its accompanying winding diagram.

EXAMPLE 5. Lay out the coils for an eight-pole two-phase unsymmetrical lap winding in a 56-slot core, connecting the pole groups in each phase in four parallel paths.

Solution

(*a*) Coils per phase = 56/2 = 28

(*b*) Referring to Table 7, there will be 4 pole groups of 3 coils each, and 4 pole groups of 4 coils each. Total pole groups per phase = (4 + 4) = 8; total coils per phase = (4 × 3) + (4 × 4) = 28

(*c*) Figure 119 shows the schematic diagram of the winding, with the phase letters and corresponding coil numbers (3 and 4) on the pole groups. Note the regular sequence of numbers 3–3, 4–4, 3–3, 4–4, etc., in accordance with Rule 3. In this four-parallel winding, each path has 7 coils in series

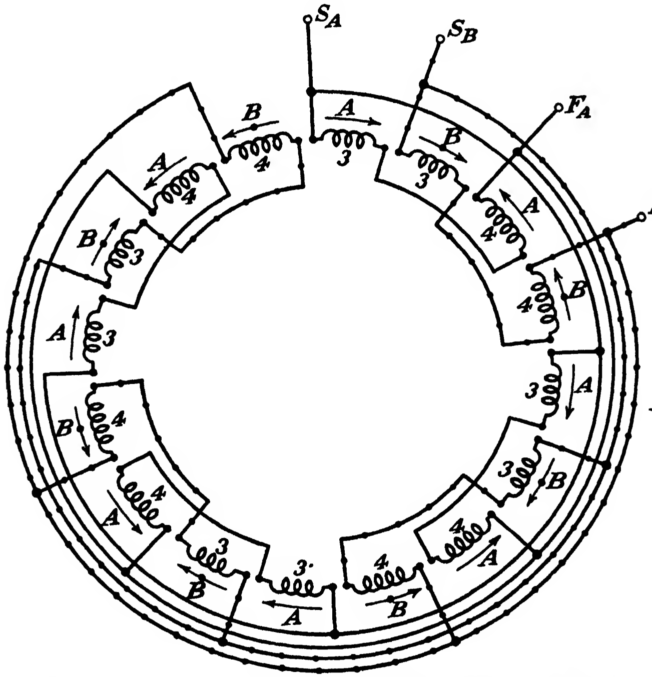


FIG. 119. Schematic diagram of an unsymmetrical 8-pole 2-phase lap winding for a 56-slot core showing the phase letters and the corresponding coil numbers on the pole groups. This is a four-parallel winding. (See Example 5.)

Rule 4. When there are twice as many pole groups in one set, X, as in the other set, Y, the two-phase winding must be arranged

so that the pole groups follow the regular sequence, X–X–Y, X–X–Y, X–X–Y, etc.

This rule is illustrated by the following example, with its accompanying winding diagram.

EXAMPLE 6. Lay out the coils for an 18-pole 2-phase, unsymmetrical lap winding in an 84-slot core. Connect all pole groups of each phase in series.

Solution

(*a*) Coils per phase = 84/2 = 42

(*b*) Determined by trial and error, this winding must have 6 pole groups of 3 coils each, and 12 pole groups of 2 coils each. Total pole groups per phase = (6 + 12) = 18; total coils per phase = (6 × 3) + (12 × 2) = 42

(*c*) Figure 120 shows the schematic diagram of the winding, with the phase letters and corresponding coil numbers (3 and 2) on the pole groups. Note the regular sequence of the numbers 2–2–3, 2–2–3, 2–2–3, etc., in accordance with Rule 4

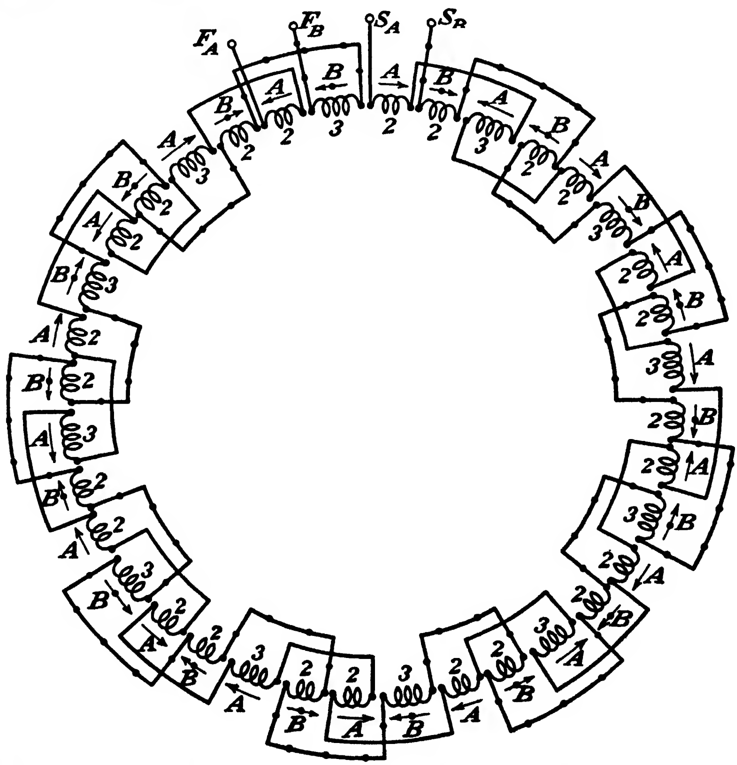


FIG. 120. Schematic diagram of an unsymmetrical 18-pole 2-phase lap winding for an 84-slot core, showing the phase letters and the corresponding coil numbers on the pole groups. All 18 pole groups of each phase are connected in series. (See Example 6.)

Unsystematic Arrangement of Unsymmetrical Polyphase Windings

The preceding two articles outline the general procedures to be followed in laying out unsymmetrical lap windings when definite combinations of slots, poles, and phases permit *systematic* arrangements of unequal pole groups. (A systematic arrangement is one in which the pole groups with different numbers of coils follow a regular order.) Unfortunately, only a limited number of slot-pole-phase combinations lend themselves to the application of rules 1 to 4, and it is for this reason that many unsymmetrical windings have *unsystematic* pole-group arrangements.

When a systematic winding arrangement is not possible, a reasonably good distribution of the pole groups must be made around the core if the machine is to perform satisfactorily. To achieve "a reasonably good distribution," it is generally necessary to space both sets of pole groups, differing by one coil, so that they follow one another with a fair degree of uniformity.

The very fact that the winding arrangement is unsystematic means, of course, that each slots-poles-phases combination must be treated as a special case; in other words, no definite rules or routine procedures can be given to apply to windings in which the differing pole groups are made to follow regular patterns, as in Figs. 115 to 120. However, if the winding layout is carefully planned with good judgment and common sense, the unsystematic distribution of the pole groups will not noticeably affect the magnetic unbalance and the resulting operation of the machine.

The following generalized method should be helpful in laying out an *unsystematic, unsymmetrical polyphase winding:* (1) Determine the number of each set of pole groups with the corresponding coils per pole group, using Tables 6 or 7, or by trial and error; (2) draw a circle, divide it into P parts, then divide each pole section into three or two parts (for three- or two-phase) to represent pole groups; (3) label each pole group with the proper phase letters; (4) arrange the *lesser number of pole groups* around the circle as uniformly as possible, making sure that each phase has the correct number of pole groups as determined in item 1; (5) in the remaining vacant spaces (*i.e.*, between those numbered in item 4), place the pole groups of the other set, the larger number, making sure again that each phase is properly represented by the number of pole groups determined in item 1; (6) connect the pole groups of each phase together, and then interconnect the phases in the usual way.

Several examples will now be worked out to illustrate the foregoing method and procedure.

EXAMPLE 7. Lay out the coils for a 6-pole 3-phase unsymmetrical lap winding in a 48-slot core. Connect the pole groups and phases in series-delta.

Solution

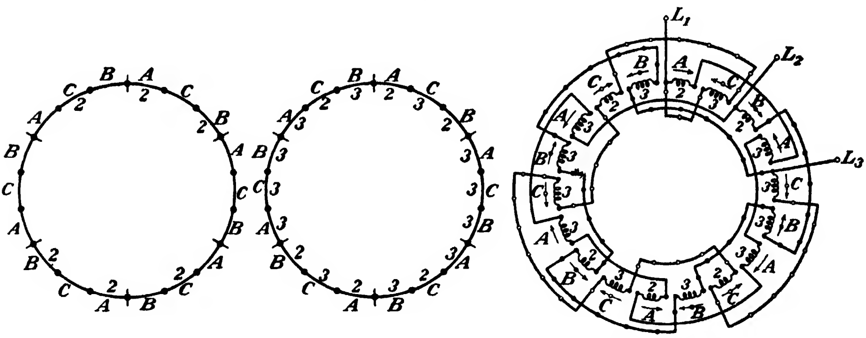
(*a*) Coils per phase = 48/3 = 16

(*b*) Referring to Table 6, there will be 2 pole groups of 2 coils each, and 4 pole groups of 3 coils each. Total pole groups per phase = (2 + 4) = 6; total coils per phase = (2 × 2) + (4 × 3) = 16

(*c*) Figure 121*a* shows a circle divided into 18 parts (six poles and three phases), with the *lesser number of pole-group sets* arranged around the circumference. Note particularly that there are *not* the same number of intervening blank spaces between those marked with the 2's (coils per pole group), but that "the distribution is reasonably good." An interesting point is that diametrically opposite spaces are paired so that there will always be exactly the same total number of coils on both sides of any arbitrarily drawn diameter; this apparent symmetry tends to maintain magnetic balance between the coils on both sides of any diameter

(*d*) Figure 121*b* shows the second set of pole-group numbers, the 3's, placed in the intervening spaces between the 2's

(*e*) Figure 121*c* shows the winding connected series-delta



(*a*) LAYOUT OF THE TWO-COIL POLE GROUP SETS
(*b*) LAYOUT OF THE TWO- AND THREE-COIL POLE GROUP SETS
(*c*) SERIES-DELTA CONNECTED WINDING

FIG. 121. Steps in the layout and connection of a 6-pole 3-phase unsystematic, unsymmetrical lap winding for a 48-slot core. (See Example 7.)

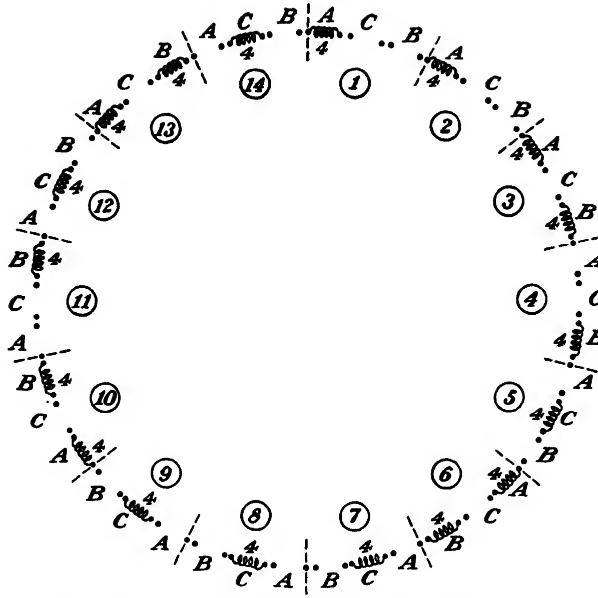
EXAMPLE 8. Lay out the coils for a 14-pole 3-phase unsymmetrical lap winding in a 144-slot core.

Solution

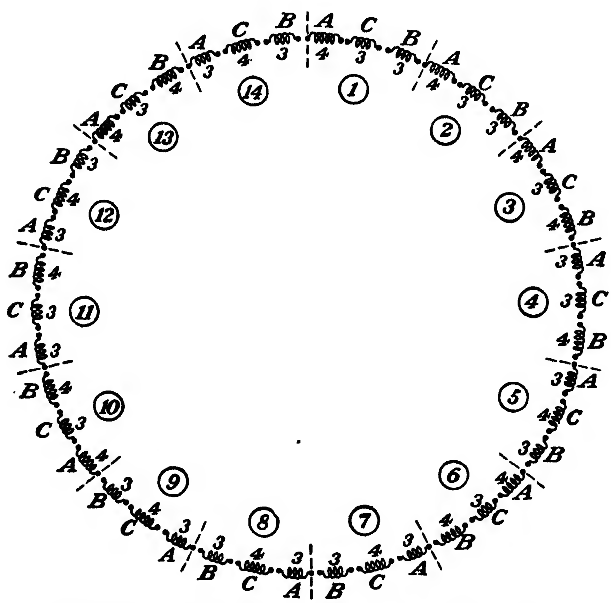
(*a*) Coils per phase = 144/3 = 48

(*b*) Determined by trial and error, this winding must have 6 pole groups of 4 coils each, and 8 pole groups of 3 coils each. Total pole groups per phase = (6 + 8) = 14; total coils per phase = (6 × 4) + (8 × 3) = 48

(*c*) Figure 122*a* shows a circle divided into 42 parts (14 poles and three phases), with the lesser number of pole-group sets arranged around the



(a) LAYOUT OF THE FOUR-COIL POLE GROUP SETS



(b) LAYOUT OF THE FOUR- AND THREE-COIL POLE GROUP SETS

FIG. 122. Steps in the layout of a 14-pole 3-phase unsystematic, unsymmetrical lap winding for a 144-slot core.

circumference. Note again that diametrical spaces are reasonably paired so that the total number of coils on both sides of any arbitrary diameter will be about the same. Also observe that this pole-group arrangement is unsystematic because there are not the same number of intervening blank spaces between those marked with the 4's (coils per pole group)

(*d*) Figure 122*b* shows the second set of pole-group numbers, the 3's, placed in the intervening spaces between the 4's

This winding is not shown with the pole groups and phases interconnected. However, four connections are possible, namely, series-star, series-delta, two-parallel star, and two-parallel delta. The student is urged to make one or more of them, using Fig. 122*b* as a starting point

EXAMPLE 9. Lay out the coils for an 8-pole 3-phase unsymmetrical lap winding in a 63-slot core.

Solution

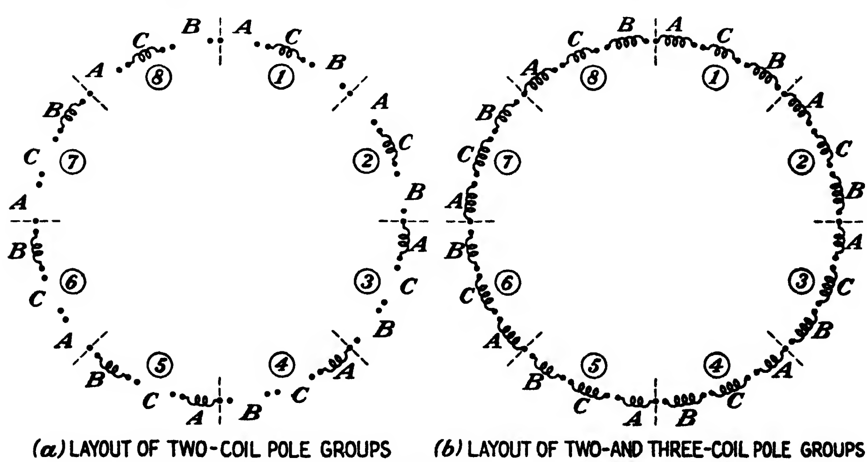
(*a*) Coils per phase = 63/3 = 21

(*b*) Referring to Table 6, there will be 3 pole groups of 2 coils each, and 5 pole groups of 3 coils each. Total pole groups per phase = (3 + 5) = 8; total coils per phase = (3 × 2) + (5 × 3) = 21

(*c*) Figure 123*a* shows a circle divided into 24 parts (eight poles and three phases), with the lesser number of pole-group sets arranged around the circumference. Note that the nine 2's, three for each phase, are distributed so that there are one or two vacant spaces between the marked pole groups at fairly regular intervals

(*d*) Figure 123*b* shows the second set of pole-group numbers, the 3's, placed in the intervening spaces between the 2's.

This winding is not shown with the pole groups and phases intercon-



(*a*) LAYOUT OF TWO-COIL POLE GROUPS (*b*) LAYOUT OF TWO-AND THREE-COIL POLE GROUPS

FIG. 123. Steps in the layout of an 8-pole 3-phase unsystematic, unsymmetrical lap winding for a 63-slot core.

nected. However, four connections are possible, namely, series-star, series-delta, two-parallel star, and two-parallel delta

Summary

1. When the number of slots in the core is a multiple of slots × phases, all pole groups have the same number of coils in series; the winding is then symmetrical.

2. When (slots/poles × phases) is not an integer, all pole groups do *not* have the same number of coils in series; the winding is then unsymmetrical.

3. All windings, whether symmetrical or unsymmetrical, must have the same number of coils per phase.

4. In unsymmetrical windings each phase has two sets of pole groups differing by one coil.

5. The number of slots in a three-phase core is always a multiple of three; in a two-phase core it is a multiple of two.

6. In unsymmetrical windings, the unequal pole groups must be distributed fairly evenly if machine operation is to be satisfactory.

7. Unsymmetrical windings may have unequal pole groups distributed around the core systematically and unsystematically.

8. A systematic arrangement is possible in three-phase windings (*a*) when there is exactly the same number of pole groups in each of the two sets; (*b*) when there are three times as many pole groups in one set X as in the other set Y.

9. A systematic arrangement is possible in two-phase windings (*a*) when there is exactly the same number of pole groups in each of the two sets; (*b*) when there are twice as many pole groups in one set X as in the other set Y.

10. When there are exactly the same number of pole groups in each of the two sets of a three-phase unsymmetrical winding, successive pole groups must have different numbers of coils.

11. When there are three times as many pole groups in one set X as in the other set Y, a three-phase unsymmetrical winding must be arranged so that the pole groups follow the regular sequence X–X–X–Y, X–X–X–Y, etc.

12. When there is exactly the same number of pole groups in each of the two sets of a two-phase unsymmetrical winding, pairs of the two different numbers of coils per pole group must follow in succession around the core.

13. When there are twice as many pole groups in one set X as in the other set Y, a two-phase unsymmetrical winding must be arranged so that the pole groups follow the regular sequence X–X–Y, X–X–Y, etc.

14. When an unsymmetrical winding (all pole groups not the same) is unsystematic (no regular sequence of pole groups), a reasonably good distribution of pole groups must be made around the core if a machine is to operate satisfactorily.

CHAPTER 14

Windings for Multispeed Motors

Polyphase induction motors generally operate with very little change in speed between no-load and full-load; it is for this reason that they are often referred to as constant-speed machines. In some applications requiring speed control down to about 50 per cent of the full-speed operation, wound-rotor motors are frequently employed; speed control is then effected through the use of a set of variable resistors in the wound-rotor circuit. Since the efficiency of wound-rotor motors diminishes rapidly as the speed is lowered, it is more economical and satisfactory to use multispeed polyphase squirrel-cage motors when the applications require several (two or more) fixed speeds. According to the American Standards Association, "A multispeed motor is one which can be operated at any one of two or more definite speeds, each being practically independent of the load." This chapter will consider the various types of winding that are employed in multispeed motors.

Two-winding Stators for Two-speed Operation

The usual single-speed polyphase squirrel-cage induction motor has a single winding that occupies all the slot space in the stator; the supply frequency, as well as the number of poles that are produced by the winding, determines the speed [see Eq. (3), Chap. 2]. If it is desired that a motor operate at two definite operating speeds from the same supply frequency, it is possible to use two independent windings that are connected to produce different numbers of magnetic poles. Such a motor must obviously be physically larger, for a given horsepower rating, than one designed for single-speed operation, because the stator slot area must accommodate two windings, only one of which is used at a time. Each of the windings can be wound and connected for any desired number of poles, so that the high speed and low speed are suited to the requirements of the application. Some of the more popular two-winding, two-speed (synchronous), 60-cycle combinations are the following: 1,800–1,200 rpm; 1,200–900 rpm; 1,200–720 rpm; 900–720 rpm; 900–600 rpm. These, as well as others, generally have a high-speed to low-speed ratio that is *not* 2 : 1, for the reason that it is

usually more economical to employ the single-winding, two-speed construction when the high speed is exactly twice the low speed.

Motors have been built with three independent windings, each one developing a different speed, but such machines are expensive and inefficient. Since the three windings must be thoroughly insulated from each other, an unusually small part of the slot area is useful for current-carrying copper. Moreover, since two windings are always idle while the motor is operating from the third at a given speed, it should be clear that an extremely limited portion of the stator core is made available to power the load. It is for this reason that motor manufacturers do not recommend three-winding, three-speed motors.

Two constructional procedures are employed in two-winding two-speed stators. In one of these the high-speed winding is first installed in the bottoms of the slots, after which the low-speed winding is placed on top of the former; the two windings are, of course, thoroughly insulated from each other. The individual windings are no different from those found in the single-winding motors previously discussed, although a special control unit must be provided so that either winding may be connected to the source. A possible alternate method is to have the same coil pitch for both windings, when the number of poles in the two speed combinations do not differ widely. Then, by a proper choice of the number of stator slots and the coil pitch, the winding design will require that each slot contain one coil-side from one winding and one coil-side from the other. This construction is discussed in the next article.

When two-winding two-speed motors are in operation, it is extremely important that the inactive winding be open-circuited. This will obviously be the situation if it is star-connected. However, when a delta connection is employed, it is essential that the two ends corresponding to one corner of the delta be left open while that winding is idle; failure to do so could result in an objectionable circulating current in the delta because of transformer action between the idle winding and the one that is energized.

The Single-coil Pitch, Two-winding Stator

When the two speeds that must be developed by a two-winding machine do not differ greatly from each other, the coil pitch of both windings may be made the same. Under this condition the two windings will have different fractional pitches, or one winding will be full pitch while the other is fractional pitch. Moreover, the number of turns per coil will, in general, not be the same for both windings, nor will they have the same cross-sectional area. The differing conditions can, however, be compromised by designing the windings so that each slot contains one coil-side belonging to one winding and another coil-side belonging to the second

winding. To accomplish this (1) the coil pitch must be from slot 1 to another slot having an *even* number and (2) the coils of the two windings must be placed in the slots in alternate succession.

The foregoing can best be illustrated and clarified by a practical example. Assume a 72-slot stator in which are to be placed two three-phase windings, one connected for four poles and the other for six poles. The 60-cycle synchronous speeds will, therefore, be 1,800 rpm and 1,200 rpm, not too widely different. The number of slots per pole in the four-pole winding will be 72/4 = 18, and 72/6 = 12 for the six-pole winding. Since the

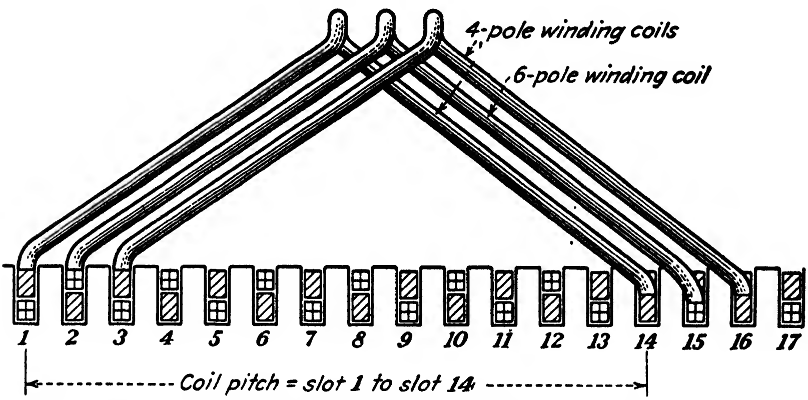


FIG. 124. Arrangement of coil-sides in the slots of a 72-slot core for a two-winding two-speed motor. Note that the coil pitch is the same for both windings, *i.e.*, slot 1 to slot 14. See Fig. 125 for winding connections.

same coil pitch is to be used for both windings, it must be from slot 1 to another having an even number, as indicated above. Selecting a coil pitch from slot 1 to slot 14, which would be suitable for this stator and the pole combinations, the four-pole winding would have fractional-pitch coils of $13/18 \times 180 = 130$ electrical degrees, and the six-pole winding would have fractional-pitch coils of $11/12 \times 180 = 165$ electrical degrees. (A coil pitch that is one slot longer than 180 degrees is equivalent to a coil pitch that is one slot shorter than 180 degrees.)

Assuming that the cross-sectional areas of the individual coils of the two windings are not equal, Fig. 124 illustrates the coil-side arrangement of several successive slots. Note that all slots have the same *total* area of copper but that top and bottom coil-sides, representing the two windings, interchange positions from one slot to the next.

Figure 125 shows one-half of one phase of each of the two, four-pole and six-pole, completely distributed windings, with the respective coils properly connected and interconnected in series. Note particularly that

(1) alternate coils are part of the same winding; (2) although the two windings are arranged in two layers, each one is equivalent to a single-layer winding; (3) each winding has a total of 36 coils (a 72-slot core with a conventional double-layer, single winding would have 72 coils); (4) the four-pole winding has three coils per pole group, and the six-pole winding has two coils per pole group.

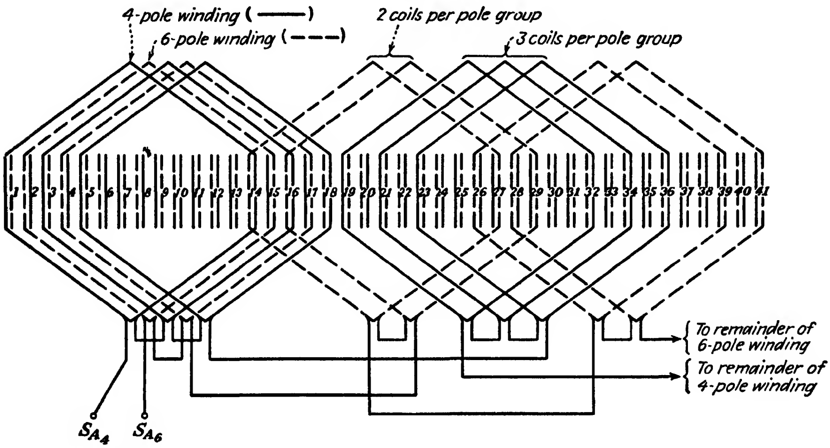


FIG. 125. Winding diagram showing one-half of one phase of each of the four-pole and six-pole windings in which the same coil span is used for both windings.

Single-winding Two-speed Motors

A polyphase winding may be connected so that the rotor will operate at either of two speeds, the higher speed being twice the lower speed. If the pole groups of *each phase* are connected so that successive magnetic polarities are *opposite—north* and *south*—at any instant, the higher speed will be developed; the winding is then said to be connected in the *conventional* manner. However, if the pole groups of *each phase* are connected together so that they create *similar* magnetic polarities—*all north or all south*—at any instant, the lower speed will be developed; the winding is then said to be connected in the *consequent-pole* manner. The principle of consequent-pole windings was discussed in Chap. 6 in the study of two-speed windings for single-phase motors and applies equally well to the operation of polyphase machines. In the actual three-phase motor unique methods of winding connections and switching are employed so that the pole groups of the various phases may be arranged for either a conventional or a consequent-pole winding. Thus, the higher speed will result when the connection is conventional, while the rotor will operate at the half-speed when the switching converts the winding to consequent-pole.

Since two-winding stators are practically always employed for two-phase two-speed operation, the discussions that follow, in which a single winding provides either of two speeds, apply only to three-phase machines.

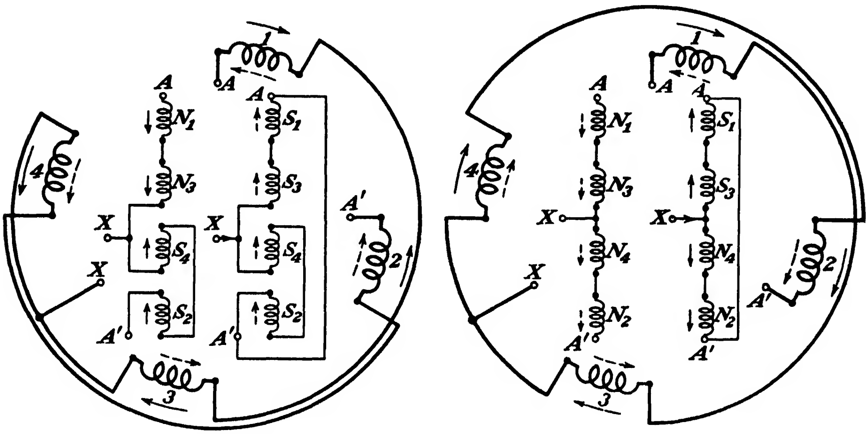
Single-winding two-speed motors have been used for over fifty years and were first manufactured in Switzerland by the Oerlikon Company as far back as 1893. Their design and construction have undergone considerable change and improvement since that time, so that modern machines are not only more efficient but also considerably smaller than were the early motors. Moreover, two- and three-winding motors are presently being built to provide as many as four or six independent speeds, two for each winding. An example of a 60-cycle six-speed motor is a stator with three windings, to develop speeds of 450, 600, 900, 1,200, 1,800, and 3,600 rpm; one winding provides the 450–900-rpm combination, a second winding develops the 600–1,200-rpm combination, and a third winding gives the 1,800–3,600-rpm combination.

The Series-parallel Principle of a Two-speed Winding

To understand how one polyphase winding may be connected to create either of two sets of magnetic polarities, one twice the other, it is first necessary to recognize the following facts: (1) When successive pole groups of each phase produce opposite magnetic polarities at the same instant, the number of poles equals the number of pole groups; (2) when all the pole groups of each phase produce the same magnetic polarities at the same instant, the number of poles is twice the number of pole groups; (3) when all three sets of magnetic poles of a three-phase winding act simultaneously on a common magnetic core, a composite set of poles is created, its number being exactly equal to the number of poles developed by *one* phase; (4) the maximum magnetic strength of each composite pole of a three-phase winding is equal to $1\frac{1}{2}$ times as much as the maximum pole strength of each pole of any one phase. Now then, since the speed of rotation of the created revolving magnetic field, and therefore the revolving rotor, is *inversely* proportional to the number of poles, it follows that a motor with a conventionally connected winding (developing P poles) will operate at a speed that is twice as great as the same machine with its winding connected consequent-pole (developing $2P$ poles).

To change a given winding from conventional to consequent-pole, and therefore from P poles to $2P$ poles, the unique *series-parallel principle* is employed. This basic principle has two variations, namely: (1) P poles are produced when all the pole groups of each phase are connected in series, while $2P$ poles are created when the same pole groups are joined in two parallel paths; (2) $2P$ poles are produced when all the pole groups of each phase are connected in series, while P poles are created when the same pole

groups are joined in two parallel paths. Figure 126 illustrates how this is accomplished for one of the phases of a four-pole three-phase winding. In both sketches the four pole groups are connected in series between terminals A and A', with diametrically opposite pole groups 1 and 3 joined in succession first, to be followed by pole groups 4 and 2; a tap X is taken from the junction between pole groups 3 and 4. However, a careful comparison of the diagrams discloses an extremely important difference between them, in so far as magnetic polarities are concerned. Assuming



(a) SERIES — CONVENTIONAL (⟶) 2-PARALLEL—CONSEQUENT-POLE (- - →)

(b) SERIES — CONSEQUENT-POLE (- - →) 2-PARALLEL— CONVENTIONAL (⟶)

FIG. 126. Sketches illustrating the series-parallel principle of the two-speed single-winding stator.

that current enters terminal A, passes through all pole groups in series, and leaves at terminal A', Fig. 126a shows that four conventional poles N_1, N_3, S_4, S_2 are produced, whereas Fig. 126b shows that the direction of the current through all the coils is the same, with pole-group polarities N_1, N_3, N_4, N_2. This means that, for the series connection, Fig. 126a will be a conventional winding with four poles, while Fig. 126b will be a consequent-pole winding with eight poles; moreover, the speed of the rotor with the conventional winding will be twice that produced by the consequent-pole winding.

Assume next that terminals A and A' are joined together in both diagrams and that current enters terminal X; the windings are then connected in two parallel paths. Referring now to Fig. 126a, it is seen that the winding is changed to consequent-pole, with pole-group polarities S_3, S_1, S_4, S_2. Fig. 126b, on the other hand, is changed to a conventional winding with pole-group polarities S_3, S_1, N_4, N_2.

It should be understood, of course, that what has been said of one phase applies equally well to the other two phases. Moreover, interconnection of the three phases to properly form a *star* or *delta* is also necessary, and this is discussed in succeeding articles.

To summarize the foregoing: (1) A winding may be changed from conventional to consequent-pole if the series-connected pole groups are reconnected in two-parallel paths; (2) a winding may be changed from consequent-pole to conventional if the series-connected groups are reconnected in two-parallel paths; (3) the series-parallel principle of the two-speed winding requires that the series connection be made with all alternate pole groups joined in series first, after which the remaining alternate pole groups are made to follow.

Torque Horsepower and Speed Requirements of Motor Applications

Polyphase induction motors must meet very rigid and exact standards of performance in modern industrial plants. This generally implies that each electrical machine must have torque, horsepower, and speed characteristics that match definite requirements of the mechanical application. Often the matter of speed control is of particular importance in production schedules which require the operator to adjust the speed to work demands or other conditions. And although the adjustable-speed d-c motor has many admirable qualities in such installations, it has been replaced largely, in recent years, by the more reliable, rugged, trouble-free a-c multispeed squirrel-cage motor.

For the purposes of standardization, motor manufacturers have divided multispeed motors into three general classes. They are (1) *constant-torque variable-horsepower* motors which develop approximately the same turning effort, or torque, regardless of the definite speed; (2) *constant-horsepower variable-torque* motors whose turning effort, or torque, is inversely proportional to the definite speed; (3) *variable-torque variable-horsepower* motors whose turning effort, or torque, varies directly with the definite speed. Each type of multispeed motor must obviously receive special design treatment, but it is of particular interest to know that, in so far as the three-phase stator windings are concerned, the following connections are generally employed:

(1) Constant-torque—Series-delta for low speed; two-parallel star for high speed

(2) Constant-horsepower—Two-parallel star for low speed; series-delta for high speed

(3) Variable-torque—Series-star for low speed; two-parallel star for high speed

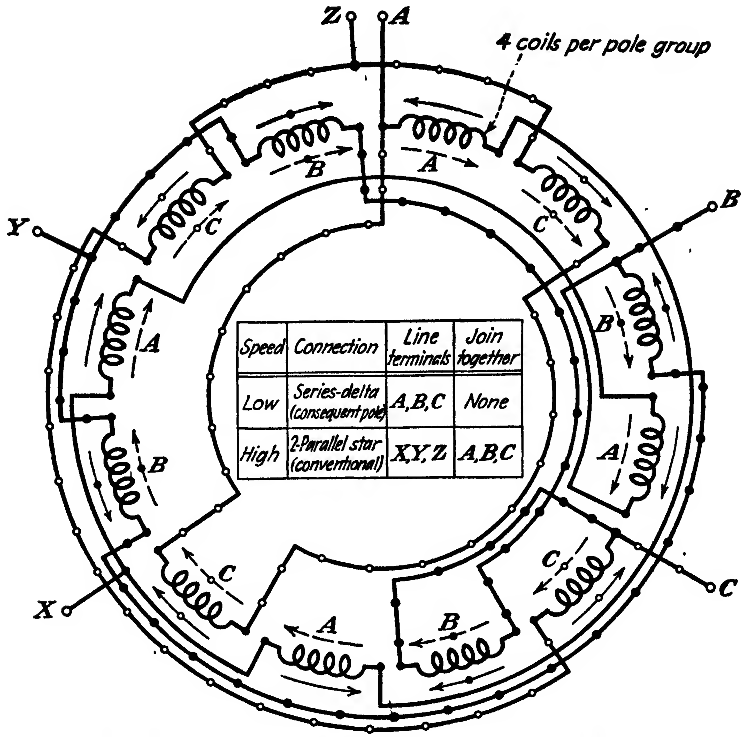
To emphasize further the importance of the foregoing three general

torque-horsepower-speed classifications, several applications are listed. Constant-torque motors are used for compressors, conveyors, stokers, textile machinery, printing presses, laundry machinery, foundry equipment, bakery machinery, and most machine tools. An excellent example of the constant-horsepower motor is a lathe, which must develop considerable torque at low speed to take a heavy roughing cut and much less torque at high speed for the finishing cut; the torque must, therefore, be inversely proportional to the speed, and the drive requires a constant-horsepower motor. Other examples are boring mills and special machine tools. For such applications as fans, blowers, and centrifugal pumps, it is customary to use motors whose torque varies directly with the speed, *i.e.*, variable-torque motors. In such drives, the required horsepower increases approximately as the cube of the speed.

The Constant-torque Motor—Series-delta, Two-parallel Star

The constant-torque two-speed motor is designed so that it develops the same torque at the low speed, when its winding is connected consequent-pole, as it does at the high speed, when its winding is connected in the conventional manner. To accomplish this, the three phases are joined together to form a *series-delta* for the low speed and a *two-parallel star* for the high speed. Although the theory of the arrangement is beyond the scope of this book it can be stated that such a condition is brought about (1) by causing the flux per phase in the series-delta connection to be 73 per cent greater than in the two-parallel star connection and (2) by making the rotor current in the two-parallel star connection 73 per cent greater than in the series-delta connection. Since torque is a function of both flux and rotor current, it is seen that the torque is the same at both speeds. Moreover, since the horsepower output of a motor depends upon torque *and* speed, it is seen that the constant-torque motor develops twice as much horsepower at the high speed as it does at the low speed.

Figure 127 is a schematic wiring diagram of a two-speed constant-torque winding in which the low-speed connection is series-delta (consequent-pole) and the high-speed connection is two-parallel star (conventional). The principle previously discussed should be helpful in tracing the diagram, which is for a 48-slot stator wound for eight-pole, four-pole operation. On 60 cycles this would give a 900–1,800-rpm combination of speeds. In practice, a six-bladed double-throw switch would have to be provided, with three terminals on one side and six terminals on the other; with the switch thrown to the three-terminal side, the motor would run at the low speed, while high speed would be attained with the switch closed on the six-terminal side. Figure 128 illustrates the switch connections for the motor.



Speed	Connection	Line terminals	Join together
Low	Series-delta (consequent pole)	A,B,C	None
High	2-Parallel star (conventional)	X,Y,Z	A,B,C

FIG. 127. Wiring diagram of a two-speed constant-torque winding for a 48-slot three-phase motor. Trace full arrows under the pole groups for the high-speed connection and the dashed arrows for the low-speed connection. This is a 900–1,800-rpm winding on 60 cycles.

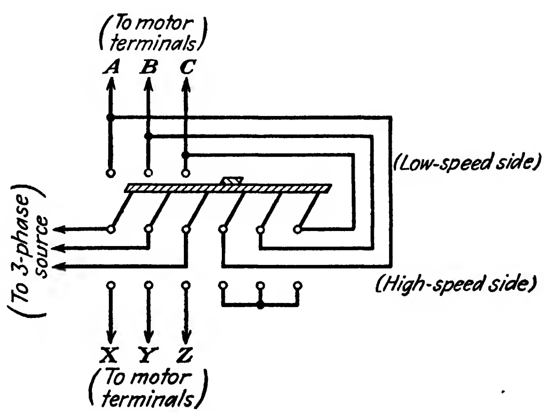
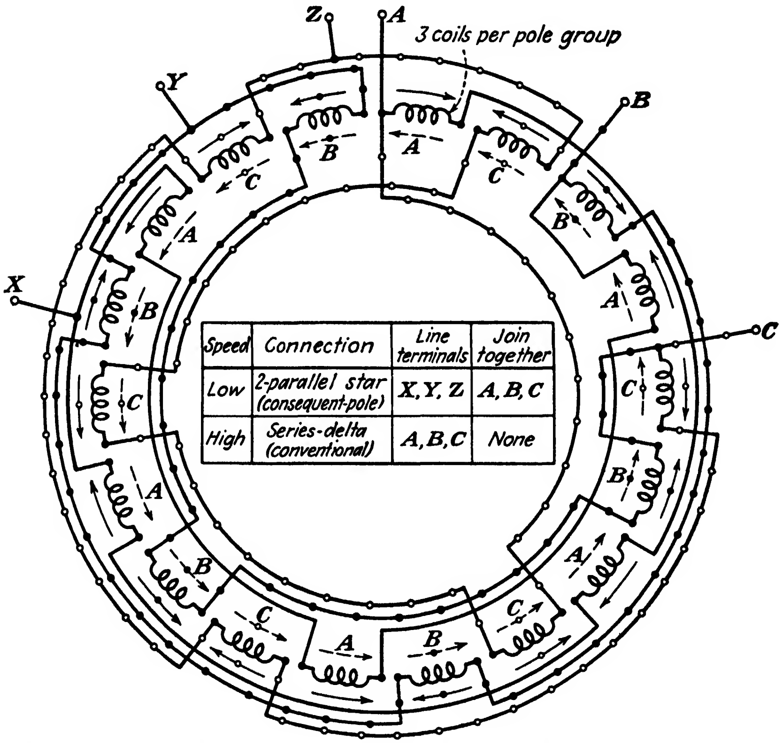


FIG. 128. Switch connections for the two-speed motor whose winding diagram is shown schematically in Fig. 127.

The Constant-horsepower Motor—Two-parallel Star, Series-delta

The constant-horsepower two-speed motor is designed so that it develops twice as much torque at the low speed, when its winding is connected consequent pole, as it does at the high speed, when its winding is connected in the conventional manner. To accomplish this, the three phases are joined together to form a *two-parallel star* for the low speed and a *series-*



Speed	Connection	Line terminals	Join together
Low	2-parallel star (consequent-pole)	X, Y, Z	A, B, C
High	Series-delta (conventional)	A, B, C	None

FIG. 129. Wiring diagram of a two-speed constant horsepower winding for a 54-slot three-phase motor. Trace full arrows under the pole groups for the high-speed connection and the dashed arrows for the low-speed connection. This is a 600–1,200-rpm winding on 60 cycles.

delta for the high speed. Such a condition is brought about (1) by causing the flux per phase in the two-parallel star connection to be 131 per cent greater than in the series-delta connection and (2) by making the rotor current in the series-delta connection 15½ per cent greater than in the two-parallel star connection. Again, since torque is a function of both flux and rotor current, the low-speed torque, T_{LS}, will be twice the high-speed torque, T_{HS}. Thus,

$$T_{LS} = (2.31)(1/1.155)T_{HS} = 2T_{HS} \text{ or } T_{HS} = (1/2.31)(1.115)T_{LS} = 0.5T_{LS}$$

Remembering that horsepower depends upon both the torque and speed, it follows that the low-speed and high-speed horsepowers will be equal.

Figure 129 is a schematic wiring diagram of a two-speed constant-horsepower winding, in which the low-speed connection is two-parallel star (consequent-pole) and the high-speed connection is series-delta (conventional). The stator represented by the diagram has 54 slots and is wound for six-pole twelve-pole operation; on 60 cycles this would give a 600–1,200-rpm combination of speeds.

The Variable-torque, Variable-horsepower Motor—Series-star, Two-parallel Star

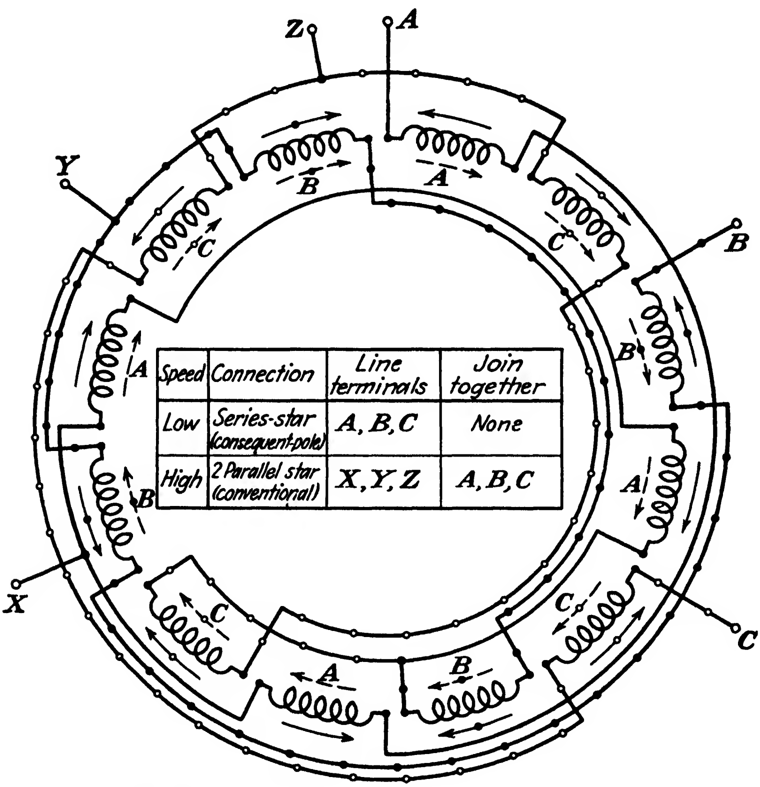
The variable-torque, variable-horsepower two-speed motor is designed so that it develops twice as much torque and four times as much horsepower at the high speed, when its winding is connected conventional, as it does at low speed, when its winding is connected consequent-pole. To accomplish this, the three phases are joined together to form a *series-star* for the low speed and a *two-parallel star* for the high speed. Such a condition is brought about (1) by causing the flux per phase to remain the same in both connections but (2) by making the rotor current in the two-parallel star twice as much as it is in the series-star connection. As a result, the high-speed torque will be double the low-speed torque; moreover, the high-speed horsepower will be four times the low-speed horsepower.

Figure 130 is a schematic wiring diagram of a two-speed variable-torque, variable-horsepower motor, in which the low-speed connection is series-star (consequent-pole) and the high-speed connection is two-parallel star. The stator represented by the diagram has 60 slots and is wound for four-pole, eight-pole operation; on 60 cycles this would result in a 900–1,800-rpm combination of speeds.

Induction Motor Windings for More Than Two Definite Speeds

Some polyphase motor applications require more than two definite speeds; in such cases two or three stator windings are employed, each of which is designed to provide one or two of the desired speeds. Thus, in a three-speed motor it is customary to have two separate windings, with one of them arranged for conventional and consequent-pole speed operation and the other wound to give the third speed. Popular speed combinations of these two-winding three-speed motors are 1,200–1,800–3,600 rpm, 900–1,200–1,800 rpm, 600–900–1,800 rpm, 600–720–1,200 rpm, 450–600–900 rpm, 450–720–900 rpm, 600–900–1,200 rpm, and others. In each of the listed groupings, the two speeds that bear a ratio of 2 to 1 are served by the conventional and consequent-pole winding, while a single-speed winding produces the third speed.

Four-speed motors generally have two conventional and consequent-pole windings, each one designed for one pair of speeds having a ratio of 2 to 1. Standard speed combinations are 600–900–1,200–1,800 rpm, 360–600–720–1,200 rpm, 450–600–900–1,200 rpm, and others.



Speed	Connection	Line terminals	Join together
Low	Series-star (consequent-pole)	A, B, C	None
High	2 Parallel star (conventional)	X, Y, Z	A, B, C

FIG. 130. Wiring diagram of a two-speed variable-torque, variable-horsepower winding for a 60-slot three-phase motor. Trace the full arrows under the pole groups for the high-speed connection and the dashed arrows for the low-speed connection. This is a 900–1,800-rpm winding on 60 cycles.

Motors that must develop five or six definite speeds have three independent stator windings. Such machines are expensive to build and quite inefficient in operation. Moreover, they are physically much larger than single-winding motors that have the same maximum horsepower ratings; in addition, they require elaborate, complicated control equipment. They are made in limited numbers and are used only where the cost, efficiency, size, and complex controls are incidental to the requirement of many definite speeds.

When two or more windings are employed in a stator for multispeed motors, the control equipment must be designed so that the winding that is not in use is completely open-circuited while the other is energized. This is an extremely important requirement. Remembering that windings in the same stator core are inductively coupled, transformer action exists between them. This implies that the winding that is energized and in service acts like the primary of a transformer, with the idle winding as the secondary. Therefore, if the secondary has a closed path, so that induced voltages can produce a current flow, unnecessary heating and retarding torque will be developed. Obviously, series-star-connected windings are open-circuited so that no special precautions are necessary in such cases. However, the two connections used in multispeed windings that are susceptible to transformer currents are the series-delta and the two-parallel star. In both of these, provision is generally made in the switching equipment to open-circuit the windings properly while they are not in use; in the delta connection, one of the junctions is opened, *i.e.*, a corner of the delta is disconnected; in the two-parallel star, the star point and one junction are disconnected.

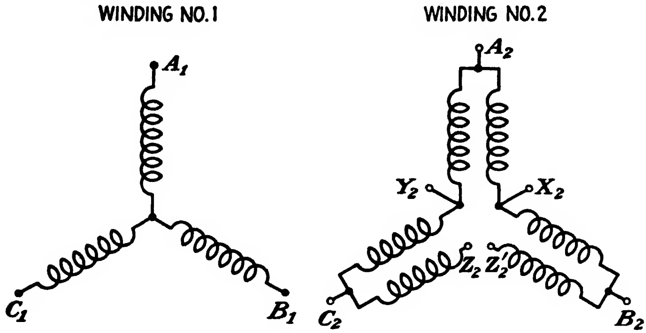
The foregoing discussion will now be illustrated by several typical simplified, two-winding multispeed wiring diagrams and their accompanying tables of connections. A properly designed speed-control unit would, of course, be a necessary part of each motor installation and would make the connections indicated by each of the tables. Note particularly that one of the two windings is always "out of service" when the other is energized and that the idle winding is open-circuited, so that it does not present a closed path for currents due to transformer action.

Figure 131 is a simplified sketch for a two-winding three-speed motor having constant-torque, variable-horsepower characteristics. Note that one independent winding serves for the *low* speed, while the conventional and consequent-pole winding provides the medium and high speeds. Obviously, the actual speeds of the motor will be determined by the supply frequency and the numbers of poles created by the windings.

Figure 132 represents a simplified sketch for a two-winding four-speed motor having constant-torque variable-horsepower characteristics. In this arrangement each winding provides two speeds; winding 1 gives the low and third speeds, while winding 2 produces the second and high speeds.

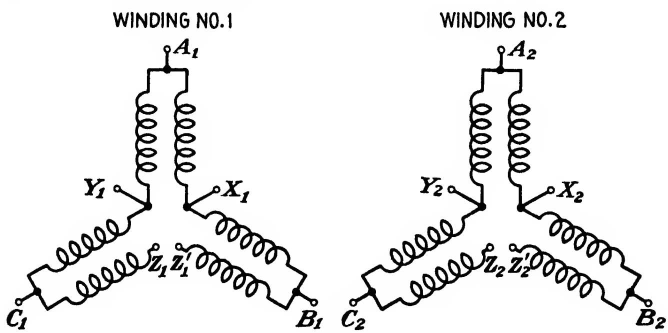
The simplified sketch of Fig. 133 is for a two-winding three-speed motor that develops constant-horsepower variable-torque characteristics. It is interesting to note that winding 1 is open at C_1C_1' when not in use. Points C_1C_1' are joined together only when winding 1 is in service, representing one corner of the delta on the high speed and part of the neutral on the low speed.

A two-winding four-speed wiring sketch is shown in Fig. 134. A motor operating with the connections indicated would have constant-horsepower



Speed	Winding	Connection	Line terminals			Join together
			L_1	L_2	L_3	
Low	1	Series-star	A_1	B_1	C_1	None
Medium	2	Series-delta	X_2	Y_2	Z_2Z_2'	None
High	2	2-Parallel star	A_2	B_2	C_2	X_2, Y_2, Z_2, Z_2'

FIG. 131. Simplified sketch for a two-winding three-speed motor having constant-torque, variable-horsepower characteristics.

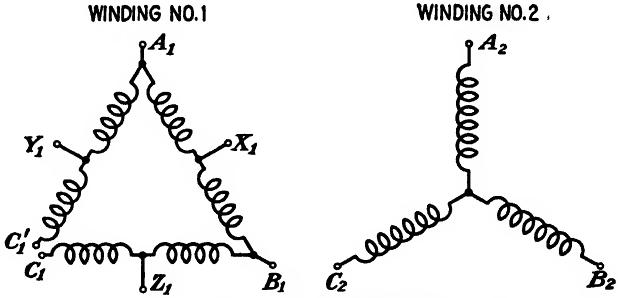


Speed	Winding	Connection	Line terminals			Join together
			L_1	L_2	L_3	
Low	1	Series-delta	X_1	Y_1	Z_1Z_1'	None
Second	2	Series-delta	X_2	Y_2	Z_2Z_2'	None
Third	1	2-Parallel star	A_1	B_1	C_1	$X_1 Y_1 Z_1 Z_1'$
High	2	2-Parallel star	A_2	B_2	C_2	$X_2 Y_2 Z_2 Z_2'$

FIG. 132. Simplified sketch for a two-winding four-speed motor having constant-torque, variable-horsepower characteristics.

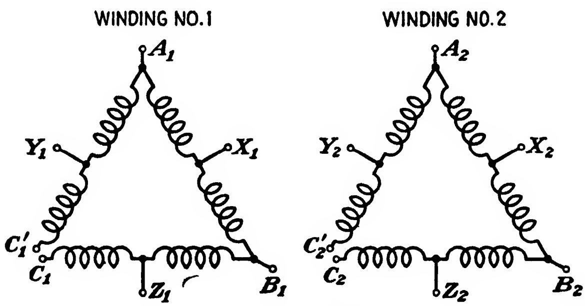
variable-torque characteristics. Both windings are essentially similar. Observe that one corner of the delta is open-circuited when that winding is idle; it is closed only when the winding is energized either to form a series-delta or a two-parallel star.

Figure 135 represents the wiring connections for a two-winding three-speed motor that has variable-torque variable-horsepower characteristics.



Speed	Winding	Connection	Line terminals			Join together
			L_1	L_2	L_3	
Low	1	2-Parallel star	X_1	Y_1	Z_1	$A_1 B_1 C_1 C_1'$
Medium	2	Series-star	A_2	B_2	C_2	None
High	1	Series-delta	A_1	B_1	$C_1 C_1'$	None

FIG. 133. Simplified sketch for a two-winding three-speed motor having constant-horsepower, variable-torque characteristics.

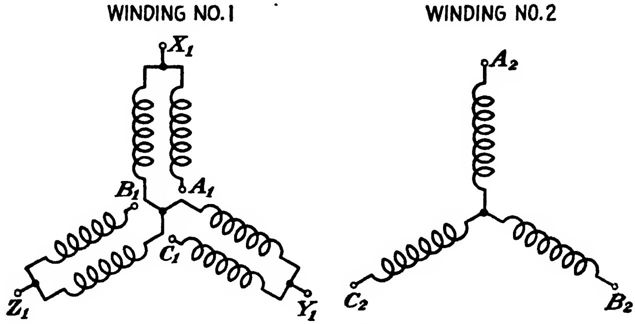


Speed	Winding	Connection	Line terminals			Join together
			L_1	L_2	L_3	
Low	1	2-Parallel star	X_1	Y_1	Z_1	$A_1 B_1 C_1 C_1'$
Second	2	2-Parallel star	X_2	Y_2	Z_2	$A_2 B_2 C_2 C_2'$
Third	1	Series-delta	A_1	B_1	$C_1 C_1'$	None
High	2	Series-delta	A_2	B_2	$C_2 C_2'$	None

FIG. 134. Simplified sketch for a two-winding four-speed motor having constant-horsepower, variable-torque characteristics.

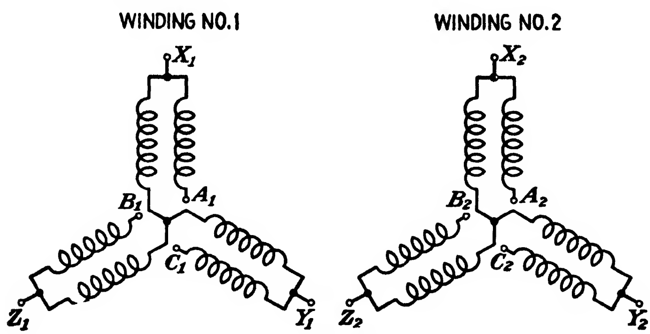
Of special importance is the fact that points A_1, B_1, C_1 in winding 1 are open-circuited when winding 2 is in service for medium speed. Winding 1 is used for the low or high speeds, under which conditions points A_1, B_1, C_1 are connected to the line terminals (low speed) or are joined together to form a second star point (high speed).

The final sketch in this set, Fig. 136, shows the connections for a two-winding four-speed motor that develops variable-torque variable-horse-



Speed	Winding	Connection	Line terminals			Join together
			L_1	L_2	L_3	
Low	1	Series-star	A_1	B_1	C_1	None
Medium	2	Series-star	A_2	B_2	C_2	None
High	1	2-Parallel star	X_1	Y_1	Z_1	$A_1 B_1 C_1$

FIG. 135. Simplified sketch for a two-winding three-speed motor having variable-torque, variable-horsepower characteristics.



Speed	Winding	Connection	Line terminals			Join together
			L_1	L_2	L_3	
Low	1	Series-star	A_1	B_1	C_1	None
Second	2	Series-star	A_2	B_2	C_2	None
Third	1	2-Parallel star	X_1	Y_1	Z_1	$A_1 B_1 C_1$
High	2	2-Parallel star	X_2	Y_2	Z_2	$A_2 B_2 C_2$

FIG. 136. Simplified sketch for a two-winding four-speed motor having variable-torque, variable-horsepower characteristics.

power characteristics. Note that both windings are similar, giving a progression of speeds from low to high as the controller switches from winding 1 to 2 to 1 to 2.

Multispeed Motors Having Wound Rotors

Squirrel-cage rotors are generally used in multispeed motors. In modern machines these are most frequently constructed by the highly developed cast-aluminum process in which molten aluminum is forced under pressure into molds containing stacks of slotted steel laminations. A set of aluminum bars and two short-circuiting end rings constitute the winding in each such rotor. Often, projecting fins are cast onto the end rings to provide a fanning action, for cooling purposes, while the rotor is revolving. Figure

FIG. 137. Cast-aluminum type of squirrel-cage rotor. (*Reliance Electric and Engineering Co*)

137 (left) depicts a common construction of cast-aluminum rotor before the shaft is pressed into the center hole, with the photograph on the right illustrating the aluminum-bar and end-ring winding only. (The latter was made by placing a completed rotor in an acid bath and dissolving out the iron)

The number of poles that are formed on a squirrel-cage rotor is always the same as that created by its stator; for this reason, therefore, it may be used in any induction motor regardless of whether the stator winding is designed for single-speed or multispeed service. However, since the resistance of a squirrel cage is fixed, and nothing can be done to alter its value, speed control and starting-torque variations are not practicable. This is obviously a disadvantage of the squirrel-cage type of multispeed motor where it may be desirable, for example, to modify the speed in steps between definite upper and lower values. Moreover, starting torque being mainly determined by the rotor resistance, it should be clear that torque requirements cannot always be met at every starting position.

To overcome the disadvantages of the squirrel-cage rotor for the purposes of speed control and starting-torque adjustments in multispeed motors, the wound rotor may be employed. The latter can be used only in two-speed motors whose single-winding stators are designed for conventional and consequent-pole operation. The rotor winding must have coils whose pitch is very nearly the same as that on the stator, because

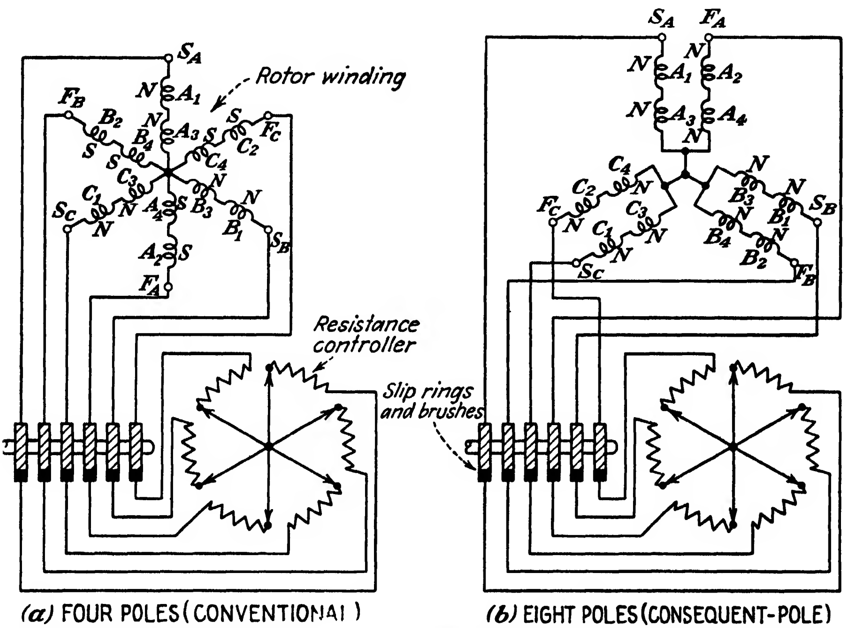


Fig. 138. Wiring diagrams showing how the polarities of a rotor winding adjust themselves to the stator connections in a single-winding two-speed motor.

rotor poles are now formed in accordance with standard winding connections. It should be clear in this respect that a wound-rotor motor will produce no torque and will not run if the number of formed rotor poles differs from that produced on the stator.

Recognizing the fact that the rotor is inductively coupled to the stator (stator and rotor are strictly the primary and secondary of a transformer), both will develop the same number of magnetic poles if their coil pitches are approximately equal. Thus, when the stator is producing four conventional poles, the rotor will do likewise; also, if the stator creates eight poles when connected consequent-pole, the rotor will respond with eight poles. Figure 138 illustrates one method of connecting a four-pole eight-pole rotor winding to six slip rings and a resistance controller. In wiring diagram Fig. 138*a*, the three phases A, B, C are shown connected to form

a six-pointed star, with the phase ends joined to the revolving slip rings; brushes riding on the rings connect to the resistors in a six-unit controller. Note that each phase produces four poles, two *north* on one side of the star point and two *south* on the other side. In this diagram the stator is presumably arranged for the four-pole conventional connection. In Fig. 138*b* the stator is assumed to be converted to consequent-pole for eight poles;

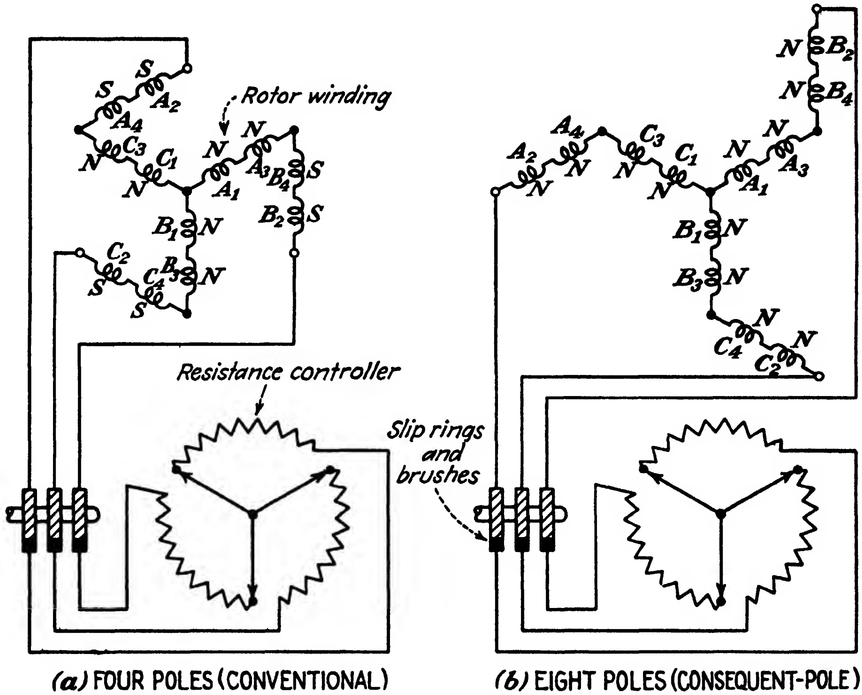


FIG. 139. Wiring diagrams showing how the polarities of a rotor winding adjust themselves to the stator connections in a single-winding two-speed motor.

the rotor, therefore, creates eight poles. Observe that the *south* poles of Fig. 138*a* are turned through 180 electrical degrees in Fig. 138*b*, so that each phase now produces four *north* and four *south* poles, *i.e.*, eight poles. In both sketches the resistance controller may be rotated to include the proper value of rotor resistance, for the purpose of adjusting the speed or starting torque. For example, the speed may be varied between the high and low definite speeds or to a value below the low speed.

An alternative method that requires only three rotor slip rings may be used if it is possible to increase the cross-sectional area of the copper in the rotor winding. A diagram of connections is given in Fig. 139. The

underlying principle of this scheme is the interconnection of one-half of one phase with one-half of another, in much the same way as transformer windings are sometimes connected *zigzag*. Note that in Fig. 139*a* half of phase A is joined to half of phase B, half of phase B is joined to half of phase C, and half of phase C is joined to half of phase A; here four poles are created because the four-pole stator winding is connected conventional. When the stator winding is switched to eight-pole consequent-pole, the outer halves of Fig. 139*a* are rotated 180 electrical degrees so that their polarities reverse. Thus in Fig. 139*b* the rotor winding changes to eight-pole consequent-pole, in accordance with the requirements of the stator.

Summary

1. Polyphase induction motors operate essentially at constant speed.

2. Wound-rotor motors are frequently used if it is necessary to control the speed down to about 50 per cent of the full-speed operation.

3. Wound-rotor motors are inefficient when operated with inserted resistance in the rotor circuit for speed reduction.

4. Multispeed motors that permit operation at definite speeds are more satisfactory and economical than wound-rotor motors.

5. Squirrel-cage induction motors are sometimes designed with two stator windings, connected to provide two operating speeds.

6. Two-winding two-speed motors are physically larger, for a given horsepower rating, than those designed for single-speed operation.

7. Three-winding three-speed motors are expensive and inefficient; they are seldom used. In such machines one winding is energized at a time, the other two being idle.

8. There are two constructional arrangements of windings in two-winding two-speed motors. In the first of these, one complete winding is placed on top of the other; the coil pitches in the two windings are different, and they are completely independent of each other. In the second, the two windings are interleaved and have the same coil pitch; they are, however, connected for different numbers of poles.

9. In two-winding two-speed motors, the idle winding must be completely open-circuited when the other is energized.

10. In two-winding two-speed motors where the coil pitch is the same for both windings, the coil pitch must be from slot 1 to another slot having an *even* number.

11. As a rule, the number of turns per coil and the wire sizes are different in the two windings of a two-winding stator.

12. Single-winding two-speed motors operate so that the high speed is twice the low speed.

13. Single-winding two-speed motors operate so that at one speed the

pole groups are connected in a conventional manner, while at the other speed the pole groups are connected consequent-pole.

14. The conventionally connected motor operates at a speed that is twice as much as the same winding connected consequent-pole.

15. When successive pole groups of each phase produce opposite magnetic polarities at the same instant, the number of poles equals the number of pole groups.

16. When all the pole groups of each phase produce the same magnetic polarities at the same instant, the number of poles is twice the number of pole groups.

17. When all three sets of magnetic poles of a three-phase winding act simultaneously on a common magnetic core, a composite set of poles is created, the number being exactly equal to the number of poles developed by one phase.

18. The maximum magnetic strength of each composite pole of a three-phase winding is equal to $1\frac{1}{2}$ times as much as the maximum pole strength of each pole of any one phase.

19. The *series-parallel principle* is employed in changing a winding from conventional to consequent-pole, and vice versa.

20. There are two variations of the series-parallel principle: (1) P poles are produced when all the pole groups of each phase are connected in series, while $2P$ poles are created when the same pole groups are joined in two parallel paths; (2) $2P$ poles are produced when all the pole groups of each phase are connected in series, while P poles are created when the same pole groups are joined in two parallel paths.

21. Constant-torque variable-horsepower motors develop approximately the same turning effort, or torque, regardless of the definite speed.

22. Constant-horsepower variable-torque motors develop turning efforts, or torques, that are inversely proportional to the definite speeds.

23. Variable-torque variable-horsepower motors develop turning efforts, or torques, that vary directly with the definite speeds.

24. The torque and horsepower relations of a multispeed motor are determined by the manner in which the phases of a winding are interconnected for the definite speeds. The two usual three-phase connections are series-delta and two-parallel star.

25. The single-winding constant-torque motor is connected series-delta for the low speed, and two-parallel star for the high speed.

26. The single-winding constant-horsepower motor is connected two-parallel star for the low speed, and series-delta for the high speed.

27. The single-winding variable-torque variable-horsepower motor is connected series-star for the low speed, and two-parallel star for the high speed.

28. Motors requiring more than two definite speeds must have two or more windings. Each winding may provide one or two of the definite speeds.

29. Motors having more than two windings are seldom used because they are expensive and inefficient. Moreover, the control equipment is rather complicated.

30. When two windings are used in a multispeed motor, the control equipment must be designed so that the idle winding is completely open-circuited while the other is energized.

31. Squirrel-cage rotors are generally used in multispeed motors.

32. The number of poles that are formed on a squirrel-cage rotor is always the same as that created by its stator. Any squirrel cage will, therefore, operate in a multispeed motor.

33. The speed of a multispeed motor having a squirrel cage cannot be controlled between definite speeds or below the lowest speed.

34. For speed control and starting-torque adjustment purposes, wound-rotor motors may be used.

35. When a wound rotor is used in a multispeed motor, the rotor coil pitch must be approximately the same as the stator coil pitch.

36. If the connections of the rotor winding are such that it does not produce the same number of poles as the stator, no torque will be developed and the motor will not run.

37. Wound rotors for multispeed motors may be designed with six slip rings or with three slip rings. In both arrangements the induced voltages in the rotor windings create currents to make the rotor have as many poles as the stator. If the stator produces the conventional number of poles, the rotor does likewise; also if the stator is connected for consequent-pole operation, the rotor responds with the consequent-pole arrangement.

CHAPTER 15

Equalizer Connections in Polyphase Windings

Well-designed, carefully constructed motors operate quietly. A noisy motor, on the other hand, is generally a reliable warning of future trouble. Moreover, a machine that runs smoothly and quietly when first installed may become extremely noisy after a period of severe service. If the proper corrective measures are to be applied to a motor that is not reasonably quiet, it is first necessary to understand the causes of such faulty operation. This chapter will be concerned primarily with the use of *equalizer connections* in polyphase induction motors, to remedy noisy performance caused by a lack of mechanical symmetry or by unbalanced windings or magnetic circuits.

Induction Motor Noise and Its Causes

A motor is a revolving mechanical machine that embodies electrical and magnetic circuits. When properly designed and constructed, it will generally operate smoothly and quietly; this will be especially so if the rotor is carefully balanced and the electrical and magnetic circuits are symmetrical.

When a motor is noisy, however, the trouble may be either mechanical or magnetic, although both causes are often interrelated. Moreover, some noises are always present and cannot be reduced, while others can be corrected by proper adjustments or may even be made self-corrective. Of the purely mechanical noises, the following may be listed: windage, loose bearings, too much end play, unbalanced rotor, loose laminations, loose rotor bars on squirrel-cage rotors, and chattering brushes on wound-rotor motors. Windage noises due to cooling fans and winding projections are, of course, always present and are more pronounced at high speeds; the noise resulting from the other imperfections can usually be reduced by making the proper adjustments or repairs. High-pitched, magnetic noise results, in the main, from the rapid vibration of the laminations. This can usually be traced to a high-frequency pulsating field that is caused by an improper choice of stator and rotor slots or by the wrong skew of the rotor slots. Although the skew is fundamental to the machine design

and cannot be changed, it is possible to lessen the noise by the use of magnetic wedges.

Other common causes of noise are an air gap that is not uniform completely around the circumference, a variation in the magnetic quality of the iron, and a winding that is unsymmetrical (see Chap. 13). These imperfections usually result in current unbalance and a tendency for the rotor to vibrate and become noisy. Fortunately this difficulty may often be remedied, partially or wholly, by the proper use of equalizers in parallel-connected windings.

Noise Created by Magnetic Unbalance

An induction motor will tend to be noisy in operation if the fluxes created by the poles are unequal. Such a condition can result if the winding is unsymmetrical, if the magnetic quality of the iron is not uniform, or if the air gap is not the same completely around the circumference. In practice it is generally the latter that is mainly responsible for the faulty performance, because (1) air gaps are usually extremely short, so that a slight dimensional variation from uniformity may represent a considerable per cent variation, (2) short air gaps are difficult to adjust accurately, (3) bearings wear in service, for which reason air gap variations do appear in time, even though the original adjustments are made with care.

Consider, for example, a four-pole induction motor in which the air gap at the top is longer than that at the bottom because worn bearings have caused the rotor to drop slightly. Assume further that the four pole groups of each phase are connected in series so that the same current flows in all the coils. Since the magnetic reluctance at the top is greater than that at the bottom (the air gap is larger there), less flux will be created in the upper air gap than in the lower one. Recognizing the fact that magnetic force is proportional to the square of the flux, an unbalanced pull will be developed that will tend to force the rotor still closer to the bottom of the stator core. The rigidity of the shaft will, of course, try to prevent the slight bending action, but the opposing forces will nevertheless result in a rapid vibration of the rotor up and down, as it rotates, and considerable noise. Moreover, if this faulty operation is permitted to continue without correction, the bearings will wear more rapidly, until the rotor actually touches the stator core; complete failure then occurs.

There are two methods that will correct or forestall the foregoing difficulty. Obviously, one of them is to replace the worn bearings with new ones and accurately center the rotor in the stator bore. The other is to employ equalizers in a parallel-connected winding, the action of which is to provide a self-adjusting correction for the unbalanced magnetic pull. Since properly installed equalizers function automatically to strengthen

weak poles and weaken strong poles, induction motors will generally operate satisfactorily even when the magnetic and electrical circuits are unbalanced. Their theory is discussed in the next section.

Theory of Equalizer Connections

When the stator winding of a polyphase induction motor is energized, a magnetic field is created that revolves at synchronous speed (rpm $= 120 \times f/P$). As the poles rotate, they cut the stationary stator conductors at a constant rate. The result of this flux-cutting action is to induce voltages in the conductors that tend to oppose a current flow; these voltages are, therefore, counter emfs and are always slightly less than the impressed voltages. Since any *induced voltage* depends upon the *magnitude* of the flux that cuts a conductor, it should be clear that the value of a counter emf at any point in a stator winding will be determined by the flux at that point. Therefore, if a winding is completely symmetrical and all magnetic circuits are identical, in the sense that the reluctances of all flux paths are equal, the counter emfs in the various pole groups will be the same; under all other conditions of dissymmetry, differences will exist among the counter emfs induced in the pole groups distributed around the stator core.

Fortunately, it is this very difference in the counter emfs that can be made responsible for the automatic correction of the unequal magnetic fluxes that cause noisy operation. And, as the following discussion will show, if a winding is properly connected and equalized, the differing counter emfs will produce circulating currents that will tend to strengthen the weak poles and weaken the strong poles; that is, the fluxes under all the poles will approach an equalized condition, even though the winding is unsymmetrical or the air gap is not completely uniform around the entire circumference.

To understand how this is brought about, consider the four pole groups of one phase of a three-phase winding placed in a motor whose air gaps are unequal. Figure 140 illustrates the arrangement suggested as well as the four magnetic flux paths. On the assumption that the bearings have worn so that the rotor is closer to the lower surface of the stator core than it is to the upper surface, the counter emfs of pole groups A_1, A_2, A_3, and A_4 are arbitrarily given values of 95, 100, 105, and 100 volts, respectively (see Fig. 140*a*). Now then, if the four pole groups are connected in series, as in Fig. 140*b*, the counter emfs will add together to oppose the impressed voltage. Under this condition, the same current I will pass through *all* coils, and no corrective action is possible. ***This is true because the same value of magnetomotive force will act on magnetic circuits whose reluctances are unequal;*** in other words, the fluxes in the upper and lower parts will

not be equal because the reluctances are not equal. The motor will, therefore, be noisy.

To take advantage of the differing values of counter emf so that a corrective action will be exerted, it is necessary to connect diametrically opposite pole groups in parallel. This is shown in Fig. 140*c*, where the pole groups are connected to form a series-parallel circuit; note that A_1 is in parallel with A_3 and that A_4 is in parallel with A_2. With attention centered first upon the local actions within each parallel grouping, it is seen (1) that no independent circulating current can flow in the A_4, A_2 pair

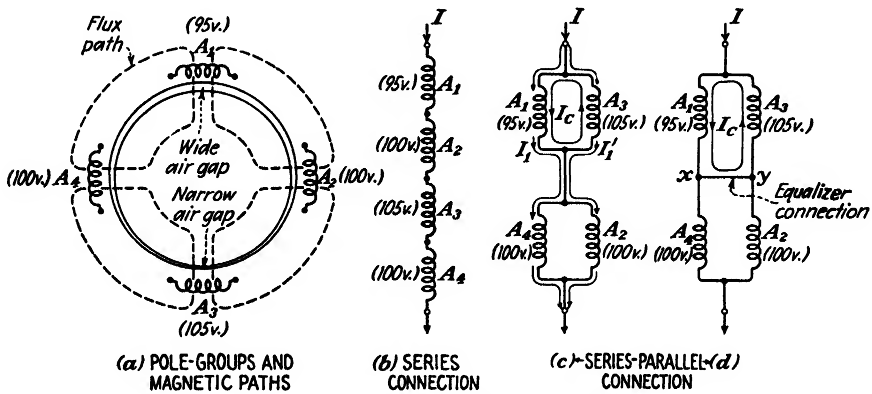


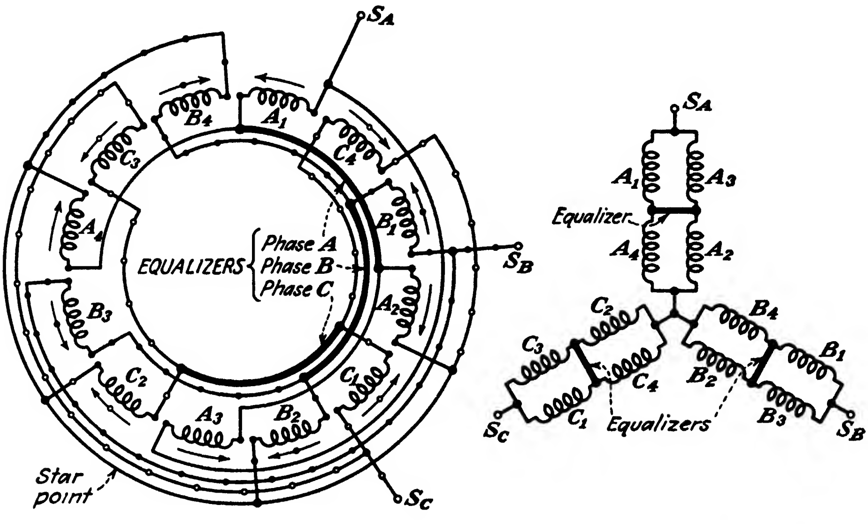
FIG. 140. Sketches illustrating the evolution of the equalizer connection in one phase of a four-pole polyphase induction motor.

because the counter emfs are equal at 100 volts, (2) that an independent circulating current will flow in the A_1, A_3 pair because there is an internal difference between the counter emfs, one being 105 volts and the other being 95 volts. Assuming that the normal current flow into the winding from the source is from top to bottom, *i.e.*, I_1 and I_1', the local circulating current I_c will be directed upward in pole group A_3, and downward in pole group A_1 *because the net counter emf of 10 volts* (105 − 95) *tends to oppose the normal direction of current.* Thus, it is seen that the current in A_1 is strengthened by the current I_c, and the current in A_3 is weakened by the current I_c. This is clearly the very effect that is desired, because the weak pole A_1 is strengthened, while the strong pole A_3 is weakened. Note particularly that differing values of counter emf, ordinarily the seat of the noise, are made to exert a corrective influence upon the dissimilar fluxes. Understand that the circulating current I_c does not actually exist as an independent current but is one of the components, an additive component in A_1, and one of the components, a subtractive component in A_3. In practice it is much more desirable to connect the pole groups as

shown in Fig. 140*d*, which is the electrical equivalent of Fig. 140*c*; in the former arrangement the standard two-parallel connection is employed with the addition of an equalizer connection $x - y$.

Typical Equalized Polyphase Windings

Figure 141 shows two simplified wiring diagrams for a four-pole three-phase two-parallel-star-connected equalized winding. Except for the



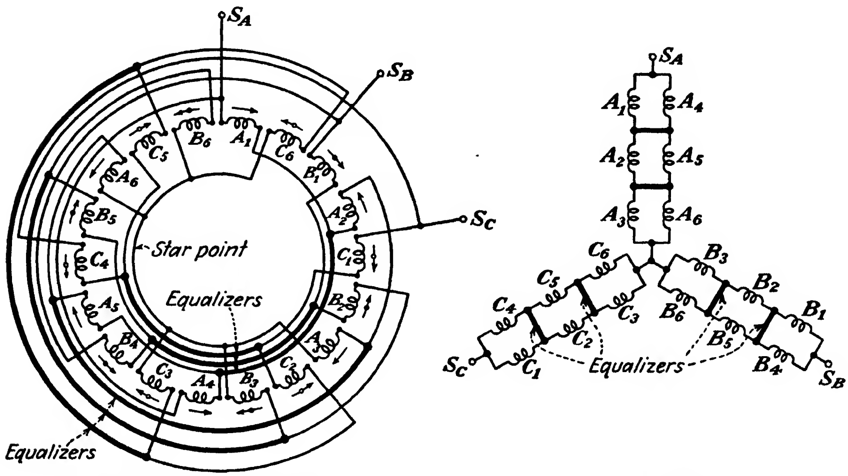
(*a*) WINDING CONNECTIONS (*b*) SIMPLIFIED SCHEMATIC DIAGRAM

FIG. 141. Wiring diagrams showing how a complete four-pole three-phase two-parallel star-connected winding is equalized.

three equalizers clearly identified in both sketches, Figs. 141*a* and *b*, the winding connections are quite similar to those previously discussed in Chap. 11. Of particular importance, however, is the unique arrangement of the pole groups in the two parallels of each phase. That is, to take advantage of the unequal counter emfs in the coils that are on opposite sides of the stator, *it is customary to pair pole groups that are diametrically opposite*. Thus, in Fig. 141*b*, it will be noted that each phase was formed into two parallel paths so that the 1–3 and the 4–2 pole groups could be directly paired by the same equalizer. In this connection it is well to recognize the fact that a winding can be equalized only if the bottom-to-bottom (B–B) and top-to-top (T–T) connection is used (see Fig. 94).

Figure 142 illustrates the wiring connections for a six-pole three-phase two-parallel-star-connected equalized winding. Observe that each phase has two equalizers and that diametrically opposite pole groups are again

paired, so that a circulating current can flow in each pair independently of any other part of the winding. *This, in fact, is the real secret of correct equalization of polyphase windings.*



(*a*) WINDING CONNECTIONS (*b*) SIMPLIFIED SCHEMATIC DIAGRAM

FIG. 142. Wiring diagrams showing how a complete six-pole three-phase two-parallel star-connected winding is equalized.

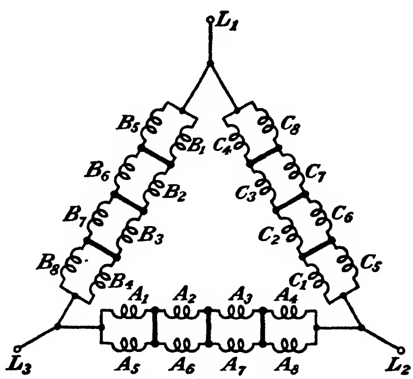


FIG. 143. Schematic diagram of an eight-pole three-phase two-parallel delta-connected winding completely equalized.

A schematic diagram of an eight-pole three-phase two-parallel-delta-connected winding is shown in Fig. 143. Note that three equalizers are needed for each phase to completely equalize the winding. Also observe how diametrically opposite pole groups are joined together in parallel by the equalizer connections.

Additional Facts Concerning Equalizer Connections

From the foregoing discussions, and from Figs. 141, 142, and 143, it should be clear that the number of equalizers per phase required to completely equalize a two-parallel-connected winding is always one less than the number of pole groups in each of the parallels; this will always be $(P/2 - 1)$. Thus, for a four-, six-, eight-, or twelve-pole winding, there will be, respectively, one, two, three, or five equalizers per phase.

Equalizer connections do not generally carry heavy currents; the currents are, in fact, much lower than those in the jumpers between pole groups. The wire size for the equalizers may, therefore, be smaller than that used for the jumpers. However, for practical reasons, and also because equalizers are usually extensions of the jumper connections, all wires that interconnect the various parts of the winding have the same wire size.

When unsymmetrical windings (see Chap. 13) are to be equalized, it is especially important that paired pole groups have exactly the same number of coils. Unless this precaution is taken, heavy circulating currents and excessive heating will result. Therefore, before attempting to use equalizers on such windings, the latter should be carefully laid out so that the principles studied in this chapter are not violated.

Two-phase windings can, of course, be equalized in essentially the same way as are three-phase windings. In applying the principles of equalizer connections to two-phase windings, each phase is treated independently. No diagrams have, therefore, been given for two-phase windings because, in so far as equalization is concerned, they are similar to those described.

For obvious reasons, equalizer connections cannot be used on two-pole windings. The two pole groups of each phase are already in parallel with each other in the usual two-parallel connection. Moreover, since the flux passes directly across the rotor diametrically, any increase in the air gap on one side, for example, is accompanied by an equal decrease on the other side. Since the reluctance of the entire magnetic circuit does not change, it follows that there is no change in the value of the flux at both air gaps. It is clear, therefore, that two-pole windings are by their very nature essentially equalized.

When a polyphase winding is completely and properly equalized, the motor will generally perform quietly and efficiently. Such a machine will, in fact, operate noiselessly and without undue heating, even if a complete set of coils in one pole group is cut out. (It is sometimes necessary to disconnect a pole group if coils are short-circuited, in order to maintain essential service.) Doing so will, of course, unbalance the line currents, but satisfactory operation may be continued.

Summary

1. Motors that are noisy in operation are either poorly designed and constructed or have received severe treatment in service.

2. It is often possible to remedy noisy motor performance by the proper use of equalizer connections.

3. When a motor is noisy, the trouble may be either mechanical or magnetic, although both causes are often interrelated.

4. The following common mechanical noises may be listed: windage, loose bearings, too much end play, unbalanced rotor, loose laminations, loose rotor bars in squirrel-cage motors, chattering brushes on wound-rotor motors.

5. High-pitched magnetic noises are due to the very rapid vibration of the laminations and may usually be traced to an improper choice of stator and rotor slots or to the wrong skew of the rotor slots.

6. Other common causes of noise are the following: air gap not uniform completely around the circumference, a variation in the quality of the iron, a winding that is unsymmetrical.

7. An induction motor tends to be noisy in operation if the fluxes created by the poles are unequal.

8. The air gap is usually very small in induction motors. It is for this reason that it is difficult to adjust accurately and to maintain uniformity in service. Air gap variations are mainly responsible for much of the noise of induction motors.

9. Considerable noise occurs in induction motors if the air gap is not uniform because, under this condition, the air gap fluxes are unequal under the several poles. Rapid vibration of the rotor then occurs, as it rotates, since an unbalanced magnetic pull is created that is opposed by the rigidity of the shaft.

10. When bearings are worn so that the air gap is not uniform, it is well to replace them with new ones. To forestall further difficulty from this defect, it is desirable to install equalizers in a parallel-connected winding when this is possible.

11. When polyphase currents flow in a stationary stator winding, a revolving field is created. This revolving field induces counter emfs in the stationary conductors.

12. If the revolving field is constant in magnitude, the counter emfs in the various pole groups will be the same.

13. Under conditions of magnetic and winding dissymmetry, differences will exist among the counter emfs in the pole groups distributed around the stator core.

14. In equalized windings, the differing counter emfs are made responsible for the self-correction of the unequal fluxes.

15. When a winding is equalized by using a two-parallel connection with equalizers, a circulating current tends to flow in each parallel pair if their counter emfs are unequal. This circulating current strengthens the weak pole and weakens the strong pole.

16. A winding can be properly equalized in a two-parallel connection if diametrically opposite pole groups are paired. This is possible only if the bottom-to-bottom (B–B) and top-to-top (T–T) connection is used. This is the real secret of correct equalization.

17. The number of equalizers per phase in a two-parallel winding is $(P/2 - 1.)$

18. In practice the wire size used for the equalizers is the same as that in the jumpers between pole groups.

19. When unsymmetrical windings are to be equalized, it is important that the paired pole groups have the same number of coils.

20. Two-phase windings can be equalized in exactly the same way as are three-phase windings.

21. No equalizer connections are possible on two-pole windings.

22. Two-pole windings are, in themselves, equalized because no flux change can occur where the flux passes across the rotor diametrically.

CHAPTER 16

Winding Changes and Calculations in Polyphase Induction Motors

It is sometimes necessary to modify an a-c armature winding in an induction motor so that the machine will perform with satisfaction when the supply voltage, frequency, or number of phases is changed. At other times it may be desirable to operate at a different normal speed, in which event the changes are often made possible by reconnecting the coils and pole groups for the new set of conditions, while in still other circumstances the existing winding must be stripped from the core and a completely new one installed. This chapter will deal with the basic principles underlying winding changes and their application to some of the more common practical problems.

Basic Principles

Changes in induction motor windings may be divided into four classes, namely, (1) voltage changes, (2) frequency changes, (3) changes in the number of phases (two-phase to three-phase and vice versa), and (4) changes in the number of poles. Each one of them may or may not be accompanied by a variation in the torque and horsepower output of the motor, although, in general, it may be said that little or no change will result in the operating performance if the maximum flux per pole and the speed are unaffected when the winding is modified.

The fundamental voltage equation [Eq. (7), Chap. 2, page 13] may be used as a basis for all winding changes if and when it is properly interpreted and applied to each individual case. In its original form the equation $E = 4.44f\phi Nk_pk_d \times 10^{-8}$ states that the voltage generated in a given a-c armature winding per phase is directly proportional to three factors, namely, (1) the supply frequency f, (2) the total flux created by each pole ϕ, and (3) the number of turns in series in each phase N. Neglecting the impedance drop in the motor winding and assuming that the counter emf is very nearly equal to the impressed voltage per phase, it is substantially correct to apply the equation to the motor winding and the source to which the latter is connected. Thus, if the voltage across the motor is increased (or decreased), without a change in the frequency f and the flux per pole ϕ, it is necessary that the number of turns in series per phase be increased

(or decreased) proportionately. Again, if the supply frequency is increased (or decreased), either of two changes may be made to obtain the same flux, namely: (1) The voltage may be increased (or decreased) in the same proportion, or (2) the number of turns in series per phase may be *decreased* (or *increased*) proportionately. Furthermore, if a motor is to be operated from a polyphase supply having a different number of phases, *i.e.*, two-phase instead of three-phase, or vice versa, the winding must either be reconnected properly and a different voltage applied or a new winding must be installed that matches the available voltage and phase system. Moreover, in all changes, account must be taken of the pitch and distribution factors k_p and k_d, although these are generally of minor importance. Each of the foregoing points will now be discussed in some detail and illustrated by appropriate examples.

Voltage Changes

One of the most common changes involves a comparatively simple reconnection of the winding so that the motor will operate at 2, 3, 4, etc., or ½, ⅓, ¼, etc., times the original voltage. In many cases this is readily accomplished by disconnecting the end connectors that join together the various pole groups of each phase and by reconnecting the winding so that the number of *parallels* in each phase increases (or decreases) in the same ratio as the voltage decreases (or increases). Thus, if a 440-volt series-star-connected winding is to be operated on 220 volts, a two-parallel star connection is made. How this is accomplished is shown schematically for one phase in Figs. 100*a* and *b*, and for the entire winding in Fig. 103. The change from one voltage to another that is twice or one-half as much is, in fact, made so frequently that manufacturers often bring out nine terminal leads for interconnection on the outside of the motor. This practice not only makes it possible for the user to connect the winding for either of two available voltages without dismantling the motor, unsoldering, and resoldering end connectors, but permits the manufacturer to build standard machines that will serve equally well when connected as indicated. Figure 104 illustrates how this is done in a six-pole motor, while Fig. 105 depicts a cutaway view of a machine of this type. Note particularly, in studying the diagrams, that the voltage per pole group remains exactly the same for either of the two connections. This is in accordance with the voltage equation, simplified to $E = kN$ in this case, to combine all constant terms ($4.44 f\phi k_p k_d \times 10^{-8}$) into a single proportionality factor k, which indicates that the voltage per phase is directly proportional to the number of turns in series per phase. Therefore, if the voltage is halved, the number of turns in series per phase is halved by using the two-parallel connection; conversely, if the voltage is doubled, the number of turns in series per phase is doubled by using a series connection.

When the voltage across a motor must be changed to one-fourth the original rating, each phase must be reconnected to have four times as many parallel paths. Obviously, the number of poles in the winding must be a multiple of four, because only in this way is it possible to have exactly the same number of coils in each path, an important requirement for proper operation. Thus, if a 460-volt motor is to be reconnected for service on 115 volts ($\frac{1}{4} \times 460 = 115$), and the original connection is series-delta, the changed winding must be four-parallel delta. The latter is permissible only if there are 4, 8, 12, 16, etc., poles, because any other number of poles such as 6, 10, 14, etc., will not permit a division of the total number of coils per phase into four equal parts. Note too that if the original connection is delta (or star), the reconnected winding must be delta (or star). Figures 92 and 102 illustrate exactly how the change is made from one, the series-delta, to the other, four-parallel delta, when there are four poles.

Table 2 (p. 128) summarizes the foregoing discussion, but, as pointed out, must be applied to each particular problem so that (1) the number of poles in the winding must be a multiple of the required number of parallels in the modified winding and (2) the same interconnection (star or delta) must be made between phases.

When a three-phase winding is reconnected from a star to a delta, with no change in the number of parallel paths, the voltage must be changed in the ratio of E to $0.58E$; conversely, if the change is made from delta to star, with no change in the number of parallels, the voltage must be changed in the ratio of E to $1.73E$. Figure 106 illustrates the voltage relationships between the star and delta connections. This additional reconnection extends the number of possible voltage changes considerably, because such a change can often be combined, with regroupings in the number of parallel paths, to yield many special voltage combinations.

An excellent example of this practice is a motor-voltage change from 240 to 208 volts, since both three-phase services are widely employed. To accomplish such a change without rewinding the motor, it would be necessary that the original 240-volt winding be a series-delta. Under this condition the voltage across one-half of each phase would be 120 volts. Now then, if a two-parallel star connection were used, the line terminal voltage would have to be $1.73 \times 120 = 208$ volts; this potential would then fulfill the important requirement that the voltage across each pole group remain the same. A change such as the one suggested here must be made carefully and systematically, if errors are to be avoided; this usually involves the drawing of a simple, properly labeled diagram and tagging the winding terminal points correspondingly. The following procedure, in connection with Fig. 144, will indicate a well-planned sequence of operations that should prove helpful for this problem as well as others of a similar nature. (1) After dismantling the motor, locate the corners

of the delta; these may be readily traced from the line terminal leads (see Fig. 144*a*). (2) Disconnect the corners of the delta and label the start and finish points of the three phases $S_A F_A$, $S_B F_B$, $S_C F_C$ (see Fig. 144*b*). (3) Locate the three connectors, each of which joins together the two halves of each phase (see Fig. 144*b*). (4) Cut the three connectors, and carefully label each pair aa', bb', and cc', *so that they are systematically marked with respect to the terminal ends* $S_A F_A$, $S_B F_B$, and $S_C F_C$ (see Fig. 144*c*).

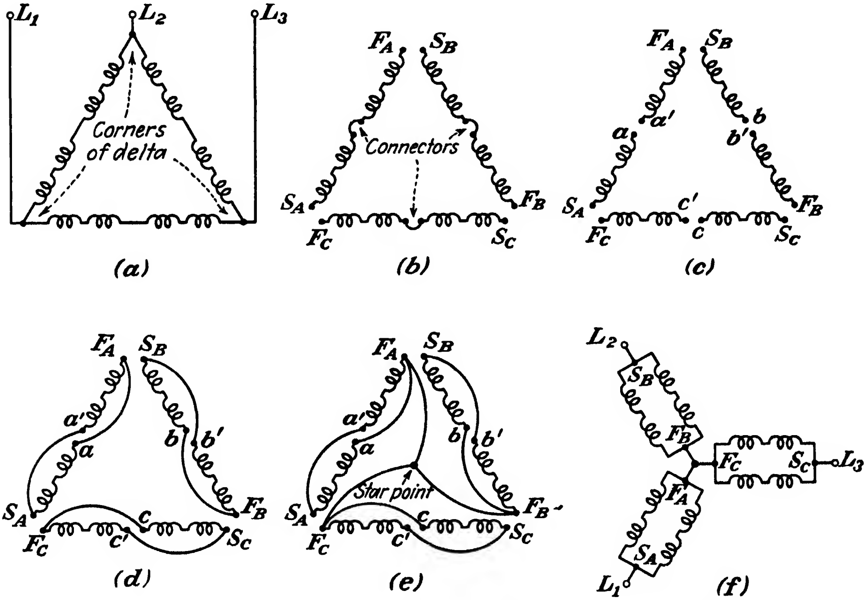


FIG. 144. Wiring diagrams illustrating a procedure for reconnecting a series-delta winding to a two-parallel star winding.

(5) Make the two-parallel connection by joining together a to F_A, a' to S_A, b to F_B, b' to S_B, c to F_C, and c' to S_C (see Fig. 144*d*). (6) Make the star connection by joining together F_A, F_B, and F_C (see Fig. 144*e*). (7) Connect the line leads to S_A, S_B, and S_C (see Fig. 144*f*).

The most desirable voltage changes are, of course, those in which the windings lend themselves to reconnection; this is true because such jobs can usually be performed simply and inexpensively. However, in many cases it is not feasible to reconnect a winding for a different desired voltage, because no combination of a star, delta, or parallels is suitable. When this happens it is generally necessary to strip the winding from the core and install a new one having the proper number of turns per phase, parallels, and star or delta interconnection. Although original winding design is beyond the scope of this book, it is nevertheless a comparatively simple matter to make calculations for a new winding that will perform satis-

factorily on a different voltage if careful note is taken of all important details as the original winding is stripped out. The data needed are coil pitch, turns per coil, size of wire, insulation materials, and kind of connection. Then, with this information as a guide, all calculations for the new winding can be made on a ratio basis. Remembering that turns in series per phase is directly proportional to voltage per phase, it is merely necessary to apply the correct ratio factor determined by dividing the new volts per phase by the old volts per phase. Moreover, as the number of wires that must be placed in each slot is increased (or decreased), the area of the wire must be decreased (or increased) proportionately; the wire size should, in fact, be as large as possible, since the motor power depends, to a great extent, upon the cross-sectional area of the copper. Minor voltage adjustments, where fractional turns appear in the final calculations, can usually be taken care of by changing the coil pitch and applying the proper pitch-factor ratio.

Frequency Changes

When a given induction type of motor is connected to a source whose frequency is more (or less) than that for which it is designed, the voltage must be increased (or decreased) in direct proportion to the frequency change, if the flux per pole is to be kept constant. The fundamental equation, Eq. (7) previously referred to, is responsible for this statement, because the impressed voltage E is directly proportional to the frequency, on the assumption that the terms $(4.44\phi N k_p k_d \times 10^{-8})$ are replaced by a proportionality factor k; *i.e.*, $E = kf$. Moreover, since the number of revolutions per minute depends upon the supply frequency [see Eq. (3), Chap. 2, page 9], it should be clear that any change in the frequency will at once result in a corresponding rise or fall in the rotational speed. Thus, for example, if a 250-volt 60-cycle 1,725-rpm induction motor is to be operated from a 50-cycle source, the emf should properly be 208 volts ($50/60 \times 250 = 208$), under which condition the speed would be about 1,437 rpm ($50/60 \times 1{,}725 = 1{,}437$).

It is generally true, however, that a frequency change is not accompanied by a corresponding voltage change in the source, in which event it is necessary to do one of two things, namely: (1) *Reconnect the winding* for the new frequency and voltage, if this is possible, or (2) strip the winding from the core and *install a new one.* Two examples will now be given to illustrate the foregoing.

EXAMPLE 1. *Reconnecting the winding.* A 230-volt 50-cycle six-pole induction motor has a stator winding that is connected three-parallel star. What change should be made in the winding if it is to operate satisfactorily from a 230-volt 60-cycle source?

Solution

Remembering that the voltage across a motor must be changed by the same ratio as the frequency is changed, it is correct to say that this ratio applies equally well to each pole group. It follows, therefore, that the volts per pole group on 60 cycles must be 1.2 × volts per pole group on 50-cycles (60/50 = 1.2). Since the 50-cycle winding is connected three-parallel-star, the 50-cycle volts per pole group is equal to 0.58 × (230/2) = 66.5. The reason for this is made clear by referring to Fig. 145*a*. Note, first, that the volts per phase is equal to 0.58 × 230 = 133, and, second, that the volts per pole group is equal to 133/2 = 66.5, because each of the parallel paths contains two pole groups in series. Hence, the volts per pole group on 60 cycles must be 1.2 × 66.5 = 79.8.

To determine whether or not a line voltage of 230 may be made to yield 79.8 volts per coil group, it must first be recognized that there are four possible connections of the pole groups in each of the phases. These are series, two-parallel, three-parallel, and six-parallel. A little thought on the matter will indicate that no star combination is possible, because the voltages per pole group are 133/6 = 22.2, 133/3 = 44.3, 133/2 = 66.5, and 133/1 = 133. Trying the delta connections, the voltages per pole group are 230/6 = 38.3, 230/3 = 76.7, 230/2 = 115, and 230/1 = 230. Since 76.7 volts per pole group is only about 4 per cent below the desired 79.8 volts, a three-parallel-delta reconnection should prove quite satisfactory. And, if the 60-cycle supply could be raised to 240 volts, the motor would operate perfectly. Figure 145*b* represents a schematic diagram of the reconnected two-parallel-delta winding. The 60-cycle speed of the motor will be about 20 per cent higher than the 50-cycle speed.

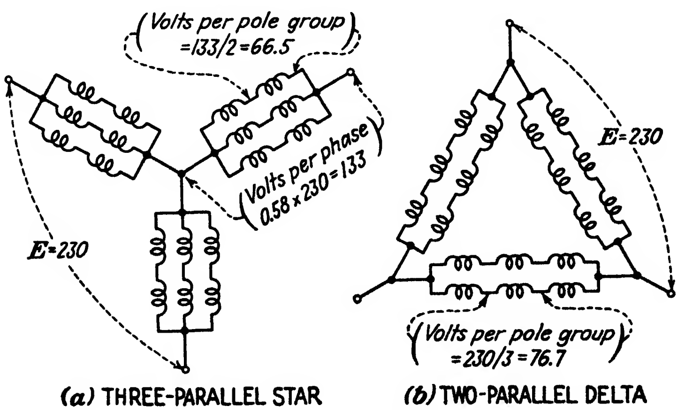


FIG. 145. Schematic diagrams showing how a 230-volt 50-cycle winding (3-parallel star) is reconnected for 230-volt 60-cycle service (2-parallel delta).

EXAMPLE 2. *Rewinding the stator.* A 220-volt 25-cycle eight-pole induction motor has a stator winding that is connected series-star. What change should be made in the winding if it is to operate satisfactorily from a 460-volt 60-cycle source?

Solution

The voltage per pole group of the 25-cycle motor is $0.58 \times (220/8) = 15.9$. Therefore, when connected to a 60-cycle source, the voltage per pole group should be $(60/25) \times 15.9 = 38.1$. Since no combination of star or delta connections will yield a voltage close enough to 38.1, it will be necessary to strip the winding from the core and install a new one. (The series-star connection would yield $0.58 \times 460/8 = 33.4$ volts per pole group, and the series-delta connection would give $460/8 = 57.6$ volts per pole group; these are the closest values to 38.1 and would not be satisfactory.) Referring again to the voltage equation, Eq. (7), it is seen that the voltage E is directly proportional to the number of turns in series per phase. Selecting a series-star connection for the new winding, which is similar to the original one, each coil should have 2.4 times as many turns as originally. When the 25-cycle winding was stripped from the core, it was found that there were 15 turns of No. 16 (2,583 circular mils) wire in each coil. Therefore, the 60-cycle winding must have $2.4 \times 15 = 36$ turns per coil. Since the wire size should be correspondingly smaller, it must have about $2{,}583/2.4 = 1{,}075$ circular mils; the nearest wire size to this value is No. 20, which has 1,022 circular mils. The 60-cycle speed will be about 850 rpm, as compared with 350 rpm when operated on 25 cycles.

Changes in the Number of Phases

Practically all large polyphase systems are, at present, three-phase. A few comparatively small two-phase systems are still in existence, although these are gradually being replaced by what may eventually become the *standard* three-phase system of generation and distribution of electric energy.

When a three-phase (or two-phase) motor must be connected to a two-phase (or three-phase) power system, it is, of course, possible to use a bank of transformers, connected in *Scott;* between motor and source; the Scott-connected transformers, having the proper ratios of transformation, change two-phase to three-phase, and vice versa. This practice is sometimes employed where a considerable amount of power is involved; and it is, for example, practicable to install the necessary transformer equipment to service standard, efficient, three-phase machines from a two-phase service.

In individual cases, however, it is often more economical to reconnect or rewind a motor for operation on an existing polyphase system; *i.e.*, a two-phase motor winding may be changed to three-phase, or vice versa. When this is done, certain well-established procedures must be followed, as explained below.

When a motor must be operated directly from a source having a different number of phases than that for which it was originally designed, it is usually necessary to strip the winding from the core and install a new one. There are two important reasons for this. In the first place, a reconnected winding always involves a changed voltage whose value does not generally match any of those available on standard polyphase systems. Secondly, the existing phase insulation between adjacent coils of different phases (see Figs. 98 and 111) is correctly placed in the original design only; therefore a change in the number of phases, which always involves a change in the number of coils per pole group, usually results in a winding that does not have the proper interphase insulation.

The following analysis will indicate why, and by what amount, the voltage must be changed when a winding is *reconnected* from two-phase to three-phase, and vice versa. Consider a stator that has S slots; the total number of stator coils will, therefore, be S. Assuming the series connection, a two-phase winding will have $S/2$ coils per phase, while a three-phase winding will have $S/3$ coils per phase. Moreover, the number of coils per pole group in a two-phase winding will be greater than the same winding reconnected for three-phase; this implies that the two-phase distribution factor k_{d2} will be less than the three-phase distribution factor k_{d3}. Now then, since the *volts per phase* is directly proportional to both the turns per phase and the distribution factor, other things remaining the same, it follows that:

$$\frac{E_{2ph}}{E_{3ph}} = \frac{S/2 \times k_{d2}}{S/3 \times k_{d3}} = \frac{3}{2} \times \frac{k_{d2}}{k_{d3}}$$

But since the average value of the ratio $k_{d2}/k_{d3} = 0.94$

Therefore

$$\frac{E_{2ph}}{E_{3ph}} = \frac{3}{2} \times 0.94 = 1.41$$

Hence

$$E_{2ph} = 1.41\ E_{3ph} \text{ and } E_{3ph} = 0.71\ E_{2ph}$$

This means that (1) if a three-phase winding is reconnected for two-phase operation, the *volts per phase* must be increased by 41 per cent; (2) if a two-phase winding is reconnected for three-phase operation, the *volts per phase*

must be decreased by 29 per cent. Thus, if a 230-volt two-phase series-connected winding is reconnected series-delta, the three-phase line voltage should be 0.71 × 230 = 163 volts. However, if the same winding is reconnected series-star, the line voltage should be 1.73 × 163 = 282 volts, because the line voltage in a star connection is 1.73 times the phase voltage. Figure 146 illustrates schematically the voltage relations that are involved in the change from two-phase to three-phase.

Again, if a 230-volt three-phase series-delta winding is reconnected for two-phase operation, the voltage should be 1.41 × 230 = 324 volts.

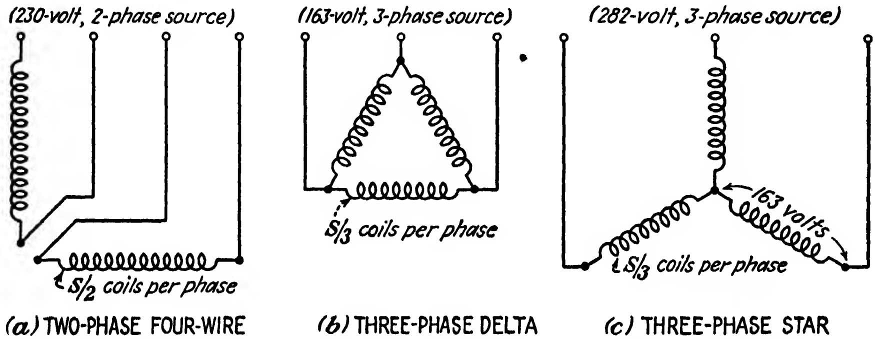


FIG. 146. Schematic diagrams illustrating the winding and voltage changes required when reconnecting from two-phase to three-phase.

Furthermore, a reconnection from three-phase series-star to two-phase requires a voltage change from 230 to 1.41 × (230/1.73) = 187 volts. Schematic diagrams illustrating these voltage changes are shown in Fig. 147, the series connections being assumed in all cases.

When a winding must be reconnected from two-phase to three-phase, or vice versa, great care must be exercised when joining together the individual coils into pole-group sections and interconnecting the various pole groups. The reconnection should, in fact, be planned with such care that the original winding is disturbed as little as possible. Assuming, then, that a reconnection is both possible and practicable, a procedure similar to the one illustrated by the following typical example should be employed.

EXAMPLE 3. A 440-volt two-phase four-pole motor is to be reconnected for operation from a 550-volt three-phase source. If the stator winding has a total of 48 coils, and each of the two phases has 24 coils in series, determine whether the reconnection is practical, and if so, illustrate by diagrams how the change should be carried out.

Solution

Since there is a total of 48 coils, a symmetrical three-phase four-pole winding is possible, because each pole group will have $48/4 \times 3 = 4$ coils in series. If a series-star connection is used, the three-phase source should have a voltage of $1.73\ (0.71 \times 440) = 540$ volts. The source voltage being less than 2 per cent high, satisfactory operation will result if the change is made as indicated.

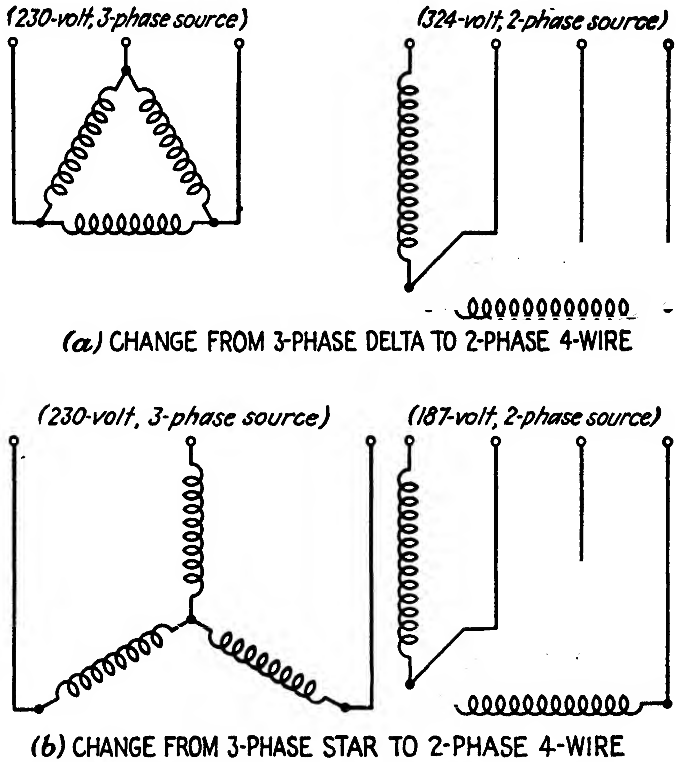


FIG. 147. Schematic diagrams illustrating the winding and voltage changes required when reconnecting from three-phase to two-phase.

Figure 148, divided into four parts, illustrates how the reconnection should be carried out. The original two-phase connection is shown in Fig. 148*a*. The first step is to remove all cross-connectors; this is represented by Fig. 148*b*, which indicates that each pole group has six coils in series. The second step is to rearrange the pole groups so that there are four coils in each; note how this was done in Fig. 148*c*, where two coils were detached from each of two adjacent pole groups and then joined in

series. The final step is to connect the 12 pole groups to form a series-star; this is illustrated by Fig. 148*d*.

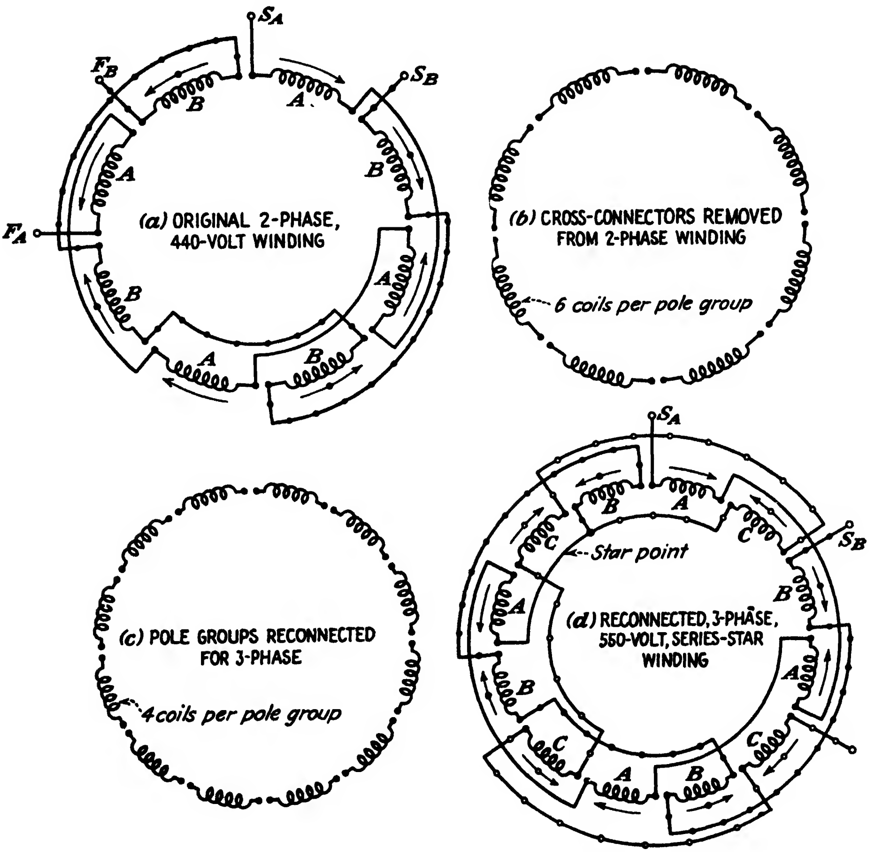


FIG. 148. Diagrams illustrating the procedure for reconnecting a 440-volt 2-phase winding for 550-volt 3-phase service. (See Example 2.)

Changes in the Number of Poles

When the number of poles in the stator winding of an induction motor is to be changed, the intention is obviously to alter the normal speed; it is assumed, of course, that the supply frequency is to be the same. Remembering that the speed of a motor is *inversely* proportional to the number of poles (rpm $= 120f/P$), it follows that a reconnection (or rewinding) of a motor, which results in an increase (or decrease) in the number of poles, will produce a corresponding decrease (or increase) in the speed. Thus, for example, a change in the number of poles from four to six will be accom-

panied by a speed *reduction* of 33⅓ per cent; again, a change in the number of poles from eight to six will mean a speed *increase* of 33⅓ per cent.

Pole changing may be accomplished in either of two ways, namely, (1) by stripping the winding from the core and installing a new one designed to operate at the proper speed from the available voltage source and (2) by reconnecting the original winding for the new pole combination so that it will perform satisfactorily when connected to the same or a different supply voltage. The second procedure is generally preferable when this is possible, since the cost of a reconnection is less than a rewind job. However, whether or not a given winding can be reconnected as indicated will largely depend upon such factors as the number of stator slots, the type of winding, the extent to which the number of poles is changed, the coil pitch, and the original winding connection (*i.e.*, its Y, Δ, or parallel combination). As a rule, it is not considered good practice to reconnect a winding if there is to be an extreme change in the number of poles or if the calculated voltage for the new connection differs too greatly from the available emf.

Assuming that it is possible to regroup all the coils in an existing stator to yield a winding for a desired pole combination, it is next necessary to determine how the changed winding must be connected for the available voltage. This calculation may be made on the basis of the fundamental principle which states that *the total flux produced by all the poles of each phase of the reconnected winding must be the same as that in the original winding.* The principle, therefore, implies that the volts per coil, directly proportional to the flux per pole ($E_c = k\phi$), must be changed *inversely* with respect to the change in the number of poles because, as the number of poles is increased (or decreased), the flux per pole must be decreased (or increased) if the total flux is to remain unchanged. Moreover, the impressed voltage per coil must be changed *directly* with respect to the pitch factor k_p because, as the pitch factor is increased (or decreased), each coil becomes more (or less) effective in generating a counter emf.

The foregoing analysis now leads to a systematic procedure to determine the voltage and type of connection that must be used when a given winding is reconnected for a different number of poles. The following steps are suggested: (1) Calculate the volts per coil in the original winding; (2) calculate the ratio of the original number of poles P_o to the new number of poles P_n, *i.e.*, P_o/P_n; (3) calculate the ratio of the new pitch factor to the original pitch factor, *i.e.*, k_{p_n}/k_{p_o}; (4) multiply together the three values obtained in 1, 2, and 3 to obtain the volts per coil in the new winding; (5) select a possible type of winding connection that will result in a value of volts per coil that closely approximates that obtained in (4).

A practical example will now be given to illustrate the method outlined above.

EXAMPLE 4. A 10-pole 3-phase 460-volt 60-cycle induction motor winding is to be reconnected for 12-pole operation from the same source of supply. Inspection of the stator discloses that there are 180 slots, the winding is double-layer lap, the coil span is 15 slots, *i.e.*, slot 1 to slot 16, and the connection is two-parallel delta. Determine the proper connection to be used for the 12-pole winding. Make schematic diagrams showing the original and the new winding connections.

Solution

(1) Total number of coils = 180; coils in series per phase in the original two-parallel-delta connection = $180/3 \times 2 = 30$; volts per coil in the original winding = $460/30 = 15.33$

(2) Ratio of $P_o/P_n = \frac{10}{12} = 0.833$

(3) Slots per pole (10-pole) = $180/10 = 18$; coil $\text{span}_{10} = (15/18) \times 180° = 150°$; $k_{p_{10}} = \sin\ (150°/2) = 0.956$; slots per pole (12-pole) = $180/12 = 15$; coil $\text{span}_{12} = (15/15) \times 180° = 180°$; $k_{p_{12}} = \sin\ (180°/2) = 1.0$; $k_{p_{12}}/k_{p_{10}} = 1/0.956 = 1.046$

(4) Volts per coil in new winding = $15.33 \times 0.833 \times 1.046 = 13.33$

(5) If a three-parallel star connection is selected, the coils in series per phase = $180/3 \times 3 = 20$; volts per phase = $460/\sqrt{3} = 266$; volts per coil = $266/20 = 13.3$

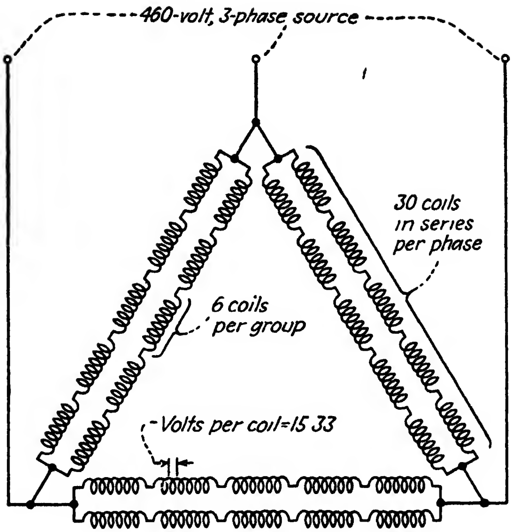
Figure 149 shows schematic diagrams for the original 10-pole and the reconnected 12-pole windings. Note particularly the calculated voltage values across the various portions of both sketches.

Other problems of a similar nature may be solved in the same way, although it should be pointed out that it is not always possible to rearrange the coils of a winding for a new pole combination and a definite voltage source. It frequently happens that no practicable parallel, star, or delta connection yields the calculated volts per coil. Under this condition it becomes necessary to rewind the stator completely for the new set of pole and voltage conditions; the procedure for making calculations for a new winding should follow a plan similar to that previously given, in which ratios are applied to the original volts per coil.

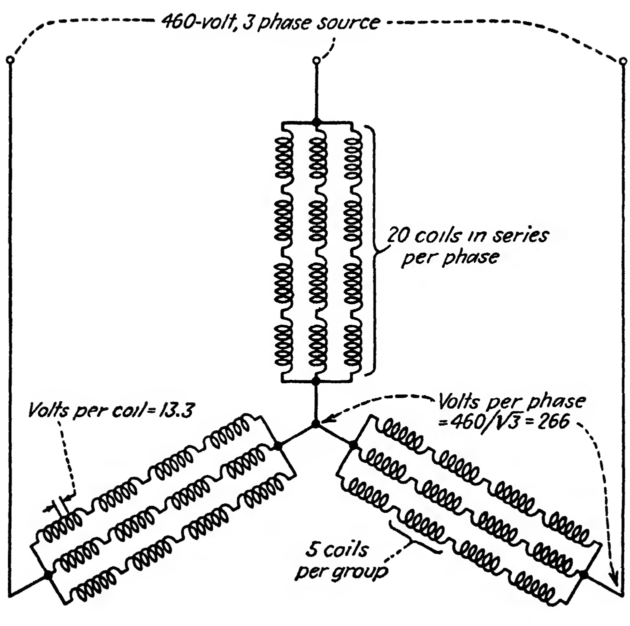
Summary

1. Windings in polyphase motors are sometimes reconnected for operation at a different supply voltage, frequency, or number of phases; infrequently the number of poles must be changed so that a new definite speed may be obtained.

2. When it is impractical to reconnect a winding for operation under



(a) ORIGINAL WINDING: 2-PARALLEL DELTA, 10-POLE



(b) RECONNECTED WINDING: 3-PARALLEL STAR, 12-POLE

FIG. 149. Schematic diagrams illustrating how a 10-pole 3-phase winding is reconnected for 12-pole operation (see Example 4 for a statement of the problem and the solution).

a new set of conditions, the stator must be stripped and a new winding must be installed.

3. There are four classes of induction-motor winding changes, namely, (1) voltage changes, (2) frequency changes, (3) changes in the number of phases, and (4) changes in the number of poles.

4. Winding changes may or may not be accompanied by variations in torque and horsepower output.

5. The basis for all winding changes is embodied in the fundamental voltage equation, Eq. (7), Chap. 2, p. 13.

6. Common winding changes involve reconnections so that a motor will operate at 2, 3, 4, etc., or ½, ⅓, ¼, etc., times the original voltage.

7. Voltage changes are readily effected through a change in the number of parallels, a change from star to delta, or vice versa, or combinations of these.

8. Manufacturers frequently bring out nine leads from a stator winding so that a motor may be connected for either of two voltages, one twice the other.

9. In general, increasing the number of parallels in a given winding requires a corresponding decrease in the supply voltage.

10. If a winding is reconnected from star to delta, with no change in the number of parallels, the voltage must be changed in the ratio of E to $0.58E$; conversely, if a winding is changed from delta to star, with no change in the number of parallels, the voltage must be changed in the ratio of E to $1.73E$.

11. When a new winding must be installed in a stator, because a reconnection will not fulfill a new set of operating conditions, calculations may be made on a ratio basis, assuming, of course, that all winding details are noted when the original winding is stripped from the core.

12. When a motor must be operated from a supply whose frequency is not the same as that for which the winding is designed, the voltage must be changed in direct proportion to the frequency change.

13. If a frequency change is not accompanied by a corresponding voltage change in the source, it may be necessary to reconnect the winding to match the available voltage, or, if this is not possible, a new winding must be installed.

14. When a three-phase motor must be operated from a two-phase source, or vice versa, a bank of transformers may be employed to change the number of phases, the winding may be reconnected for the new phase system, or a new winding may be installed.

15. If a three-phase winding is reconnected for two-phase operation, the volts per phase must be increased by 41 per cent.

16. If a two-phase winding is reconnected for three-phase operation, the volts per phase must be decreased by 29 per cent.

17. Great care must be exercised when a winding is changed from three-phase to two-phase, or vice versa. A systematic procedure should be followed in joining together the individual coils into pole groups and the various pole-group sections into phases.

18. Pole changing in a stator winding implies that the normal speed of the motor is to be modified.

19. The speed of a motor varies inversely as the number of poles.

20. Pole changing may be accomplished either by stripping the winding from the core and installing a new one designed for the new speed and voltage or by reconnecting the original winding for the new pole and voltage combination. The latter is desirable when this is practicable.

21. It is not considered good practice to reconnect a winding if there is to be an extreme change in the number of poles. A change of two poles, sometimes four, is generally permissible.

22. When a winding is reconnected for a different number of poles, the new voltage must be determined on the basis of the fundamental principle that *the total flux produced by all the poles of each phase of a reconnected winding must be the same as that in the original winding.*

23. To fulfill the principle stated above, it is necessary that a pole change be accompanied by an inverse change in the flux per pole. Also a change in the pitch factor must be accompanied by a corresponding voltage change.

24. When the calculated volts per coil in a pole-changed winding cannot be matched by any combination of parallels, or by star and delta interconnection, a new winding must be designed and installed in the stator.

CHAPTER 17

Winding Troubles: Causes, Symptoms, Locations, Remedies

Alternating-current, induction-type machines are less likely to develop trouble than those designed for d-c service. This is undoubtedly true because the difficulties arising from commutation are no longer present, and moving contacts are, for the most part, eliminated. However, because of severe and abnormal service conditions in the field, or careless manufacture and inspection in the shop, machines may occasionally operate improperly or break down completely. Among the many reasons for possible failure are: excessive heating due to overloads; poor ventilation; loose squirrel-cage connections between rotor bars and end rings; worn or carelessly installed bearings; frequent starting and stopping with excessive starting currents; objectionable surroundings such as moisture, chemical fumes, dirt, etc.; operation on the wrong voltage or frequency; improper winding connections; and many others. This chapter will attempt to point out some of the more common sources of troubles, their location, and remedies, although it should be mentioned that considerable experience with actual service conditions in the field is essential in the important and interesting occupation of "trouble-shooting."

General Kinds of Winding Troubles

Faulty operation or complete breakdown of an induction-type machine may be traced to either of two general classes of trouble, namely, mechanical or electrical. Mechanical difficulties arise from such factors as loose bearings, eccentric or bent shafts, unbalanced rotors and loose bars in the rotor slots, misalignment of the motor and load shafts; these usually lead to noisy operation and, eventually, to electrical failure. Of the latter may be mentioned such troubles as grounds, short circuits, and open circuits in the stator winding, and poor connections between rotor bars and end rings in squirrel-cage rotors; in wound rotor motors, brushes may not be making good contact with the slip rings. Other sources of electrical trouble are: low voltage which may cause a machine to run at a low speed and overheat; low frequency, although this is not likely in large distribution systems; unbalanced voltages in polyphase systems, which may result in higher-

than-normal currents; single-phase operation of polyphase motors, because a blown fuse or an actual break in one of the line wires causes the motor to operate on single-phase even though it is properly started on two- or three-phase. Still another class of electrical troubles may be occasioned by several kinds of errors made in the shop when a winding is installed. Recognizing the fact that a polyphase winding consists of a great many coils which must be properly divided into pole groups and phases and carefully interconnected with the correct polarities, parallels, and star or delta combinations, it is easy to see that carelessness in any of these operations may result in the eventual failure of the motor in service. Of the more common winding errors made in the shop, the following may be given: the various pole groups may not have the proper number of coils because of wrong counting; the polarity of one or more pole groups may be reversed; a complete phase may be reversed; one or more coils in a pole group may be reversed; the winding may not be connected for the name-plate voltage; the winding may not be connected for the name-plate speed, *i.e.*, the number of poles may be wrong.

Grounds

A *ground* in an armature winding is a direct metallic connection due to insulation failure between any copper conductor of the winding and the iron core or frame of the machine. This may be caused by defective insulation on the wire and the slot cell when the coils and insulating materials are roughly handled. Especially is this apt to happen where the coils bend around sharp corners of the laminated core ends; in other cases the insulation may become charred because of overheating of the winding. When a single ground does occur it is equivalent to having the entire metal frame as a "live wire" exposed to human contact; under this condition it is possible for one to receive a severe shock upon contact with the machine if some part of the electrical system is grounded, as is usually the case. Should two or more grounds exist in a winding, a short circuit would be formed between them through the iron core; in such cases the coil or coils between the defects would immediately become very hot and destroy the surrounding insulation. In any event it is always best to detect, locate, and correct the failure, if possible, before harm to person or damage to machine is done.

Short Circuits

As was pointed out under "grounds," a *short circuit* results when two copper conductors touch the core so that current can pass between them through the iron. More often short circuits exist in a winding without being grounded, because the insulation on adjacent wires or coils may fail

and cause a current flow in local unconventional paths. When this happens, the windings usually become very hot and may even produce smoking of the insulation; in fact, if a cold motor is connected to the line, a short-circuited coil or winding can be detected soon thereafter by its high temperature if it is touched with the hand. In practice it is sometimes necessary to maintain service even though a short-circuited coil is found to exist in the winding. The defective coil, having been located, should be completely disconnected from its pole group, after which it is necessary to make certain that a continuous path is provided around the one that is removed; following this, the short-circuited coil must be cut at some convenient point to make sure that no current can flow in it because of transformer action.

Open Circuits

An *open circuit* in a winding may result from rough handling of coils and wires or because a poor soldering job is done. In such cases nicked wires may eventually give rise to broken wires, and poorly soldered joints may cause the electrical resistance to become excessive at the contact between wire ends. Such defects are readily detected because a motor will fail to start when electric service is applied to an open-circuited winding. In rare cases a break may occur in a polyphase winding while the machine is in operation; under this condition there will be an excessive temperature just as in a motor that is single-phasing.

Improper Connections

In general winding practice, it is the custom to install all the coils in the core before they are interconnected into pole groups, phases, parallels, and star or delta combinations. The interconnection procedure must be done with great care because, with the large number of coil ends to confuse the operator, it is easily possible to make several kinds of errors. And, strangely enough, such errors, when examined in relation to available winding diagrams, are difficult to understand unless they are attributed to the careless counting of coils or the improper labeling of coil ends before the connections are made. Experience has shown that the winder must be alert against the possibility of making four kinds of improper winding connections. These are (1) combining the wrong number of coils into pole groups, (2) connecting a coil in a reversed direction within a pole group, (3) connecting a complete pole group in a reversed direction, and (4) connecting a complete phase in a reversed direction.

1. *Wrong pole grouping.* This fault results when the winder makes an error in counting coils that must be connected together into pole groups; in symmetrical windings all pole groups should obviously have the same number of coils in series. Thus, for example, all pole groups in a 72-coil

4-pole 3-phase winding should have 6 coils ($72/4 \times 3$), so that the presence of a 5-coil and a 7-coil group would indicate that an error was made in the counting of coils in two adjacent pole groups. Although a fault of this kind is not as serious as the others listed above, when such an error is made it will be found that a motor will be somewhat noisier than usual.

2. *Reversing a coil within a pole group.* The effect of connecting one of the coils within a pole group in a reversed direction with respect to its neighbors is equivalent to reducing the effectiveness of the group by two coils. The reason for this is owing to the "bucking" action of the reversed coil in its function to produce magnetism; it tends to create flux of a polarity that is opposite that of the other coils, so that it nullifies the magnetic action of one of those that are properly connected. Motors having this fault will be magnetically unbalanced and will show a tendency to get hot and be noisy.

3. *Reversing a complete pole group.* It should be clear that successive groups of coils in any one phase of a double-layer winding must create opposite magnetic polarities at the same instant, regardless of the number of parallels or type of interconnection. Particular attention in this regard is directed to many winding diagrams such as Figs. 75, 77, 79, 90, 94, 95, and others. When an error is made so that a complete pole group is reversed, the resulting magnetic field will be greatly distorted from its true uniform and symmetrical configuration. And, as before, such magnetic unbalance will manifest itself by an unusually high temperature rise and considerable noise when the motor is in operation.

4. *Reversing a complete phase.* In three-phase windings, the electrical displacement between phases must be 120 electrical degrees, and this space separation is accomplished by properly labeling the phase ends. Referring again to Figs. 77 and 78, it will be observed that the correct location of the three "start" ends S_A, S_B, and S_C definitely establishes the 120 degree relationship; this obviously means that the three "finish" ends F_A, F_B, and F_C must be represented by the completion of the respective phases as shown in Figs. 80 and 91. Now then, should the start and finish ends of any one of the three phases, say phase C, be interchanged so that they are incorrectly labeled, the electrical position of that portion of the winding would be reversed. The result would be that the reversed phase C would be 60 electrical degrees ahead of phase B and 60 electrical degrees behind phase A; in other words there would be a 60-electrical degree displacement between phases. Figure 150 illustrates schematically how the interchange of the ends of phase C establishes this, most serious, improper connection. Proceeding further with this faulty labeling, if the star connection is then made, an alternator would obviously supply a system of voltages that are 60 electrical degrees apart, and a motor would become very hot and be

extremely noisy. Moreover a delta connection would be even more serious in an alternator, because a closed path is provided for a potential difference that is twice the voltage rating per phase; the delta-connected motor would, as before, be hot and noisy.

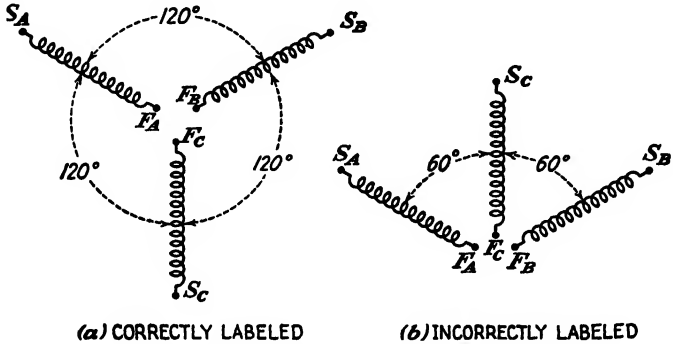


FIG. 150. Sketches illustrating the correct and incorrect labeling of the phase ends of a three-phase winding.

Symptoms of Winding Troubles

It has already been pointed out that short-circuited motor windings and those that are improperly connected will, in general, develop an excessive temperature rise and operate quite noisily. In some cases the growling noise may be very noticeable, so that trouble is immediately indicated. In still others the noise may not be particularly recognizable against the usual factory background, although it may be observed that a machine will lose speed rapidly as load is applied. Where generators are concerned, it will generally be noted that proper voltage will not be maintained with increasing values of load. Furthermore, a motor that has an open-circuited winding will not start, nor will an alternator build up voltage with a similar kind of trouble. In any event the causes for the faulty operation, as indicated by symptoms that are caused by one or more of several kinds of fault, are frequently difficult to determine. Experienced trouble shooters, however, can often diagnose and even locate a defect quite readily, but such ability comes only from many years of careful observation of large numbers and many kinds of failure.

When trouble is suspected in a motor, it is always a good practice to disconnect the load and attempt to operate it free from any countertorque. The voltage supply should be measured, bearings and lubrication should be inspected, and fuses tested. Note how the machine comes up to speed and whether or not it operates at near-synchronous speed. Observe as many mechanical details as possible, such as bracket and supporting bolts, pulley or gear, alignment, etc., making note of any points that appear

suspicious. If the machine has brushes and end rings, see that good contact is made on the rings and that the brushes do not chatter or bind in the brush holders. As the motor runs, listen carefully for unusual noises; if there is no apparent trouble, there should be a low humming sound like that made by transformers. If the rotor has a fan for cooling purposes, a whistling sound may be heard and much air may be felt as it is blown out of the machine. If the speed seems to be correct, place the hand on the motor frame to detect any unusual vibration. An excellent test is to place one end of a long rod or screwdriver on the frame while holding the other end to the ear; motor noises are transmitted to the ear and are greatly amplified in this way. Try opening the switch while the motor is running, and note if there is any appreciable reduction in noise; if not, and the motor seems to vibrate, the trouble may be purely mechanical. Another simple test is to pass the hand around the extensions of the winding as the motor runs, to attempt to detect any unusual rise in temperature. Then, after about 5 minutes or more, shut down the machine, quickly remove one of the end bells, and feel around the winding for any hot places. And, while this is being done, look carefully for any suspicious insulation failures. Of particular importance in induction machines is the air gap between stator and rotor. If this is not practically uniform, as a careful test with a thickness gauge should reveal, it is a good indication that the bearings are not properly centered or are badly worn.

If ammeters are available (the clamp-on type is excellent for this purpose), measure the no-load current in the line wires with the motor running free. In polyphase machines (two- and three-phase), the values should be nearly uniform for all phases and about 20 to 35 per cent of the full-load name-plate designation. Values that are excessive or are not approximately equal are fairly good indications that there is some sort of mechanical or electrical trouble.

Having made the foregoing preliminary inspections and tests (it is often possible to locate the fault definitely in this way), the next step is to dismantle the machine and to proceed with a further systematic series of tests to find the trouble, assuming, of course, that it has not been found. These should be made as outlined in the following discussions.

Locating Grounds

With the machine dismantled, it is necessary first to perform the "ground" test; other tests would prove useless if the winding were not thoroughly insulated from the frame, especially if the winding were grounded at more than one point, which, in effect, represents a short circuit between any two such grounded coils. One way to determine if (not where) the winding is grounded is simply to connect one side of a 110- or 220-volt test lamp circuit

to a bare (unpainted) spot on the metal frame, and to connect the other side to any one of the winding terminals. (A lamp circuit is merely a pair of power leads that has an incandescent lamp connected in series in one of the lines.) If the lamp lights up, there is a ground. Another scheme is to employ a *megger* or magneto, either of which is connected in the same way as is the lamp circuit; when a handle is turned, the *megger* will give a visual indication (a meter deflection) of the insulation resistance, while a bell in the magneto will ring if there is a ground. Still another method makes use of a special high voltage transformer that develops a secondary emf

FIG. 151. Growler used for locating short circuits and open circuits in the windings of a-c machines. (*The Martindale Electric Co.*)

of 2,500 volts or more; when the terminals are connected to the winding and frame in the usual way, a circuit breaker that is part of the device will open instantly if there is a ground.

To locate the ground it is a common practice to apply sufficient voltage between a winding terminal and ground, using the equivalent of a test lamp circuit for this purpose, until the ground is "burned out." As a rule this test will cause the insulation to smoke or an arc to form at the point of trouble. In the event that the ground cannot be found in this way, it may be necessary to open up and isolate successive sections of the winding, testing each part independently until the ground is narrowed down to a single coil. After the grounded coil has been located, it should be carefully removed from the core and either repaired or replaced by a new one.

Locating Short Circuits

It was previously stated that a short-circuited coil can usually be located by running the machine without load for a few minutes and by feeling around the winding with the hand for evidence of unusual temperature rise.

This simple procedure will frequently make it possible to point directly to the defect.

An extremely useful device for locating short circuits is a *growler*, a photograph of which is shown in Fig. 151. It consists essentially of a coil of wire wound around a laminated iron core whose surface faces are shaped and adjustable to conform with the inside surface of a stator. When in use, the growler coil is connected to an a-c source and acts as the primary of a transformer, the secondary of which is the motor winding when the device is placed into, and in contact with, the laminated stator core; the iron of the stator core completes the magnetic circuit for growler iron. To locate a short circuit, the device is slowly moved around the core as the successive coils are felt with the hand for evidence of heating; when the growler is directly over the center of the defective coil, the induced voltage in the latter will cause a high current to flow in it, since it acts exactly like the short-circuited secondary of a transformer. Another way to detect the short circuit is to observe an ammeter placed in series with the device; as it passes over the fault, the current in the primary will rise, just as it does in the secondary. Still another procedure is to lay a strip of steel, such as a hack-saw blade, over the defective coil; a strong attraction between core and strip will indicate the position of the short-circuited coil. Figure 152 illustrates the use of the growler in the stator core of a motor.

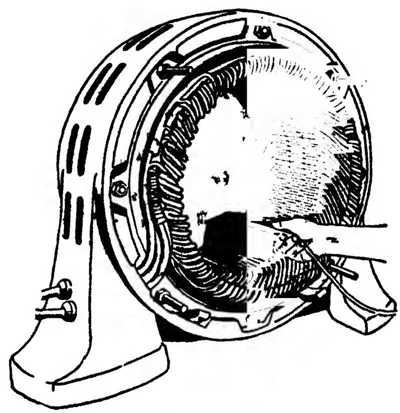


FIG. 152. Illustration showing growler of Fig. 151 in use in testing a stator. (*The Martindale Electric Co.*)

Locating Open Circuits

When there is an open circuit in a winding, current will not flow when it is connected to an a-c source. In the case of polyphase motors, therefore, the machine will not start but will behave as though it were single-phasing when the line switch is closed. Assuming that the winding is connected series-star, the open-circuited phase is readily located if the line wires are opened in succession; no spark will be noted when the wire that is joined to the open phase is disconnected. To locate the open-circuited phase in a series-delta winding, it is first necessary to disconnect one corner of the delta and then test for the continuity of each phase in succession. This may be done by using a test lamp circuit; a lighted lamp indicates a com-

plete phase, while one that is defective will show up because the lamp will not light. The portion of a winding that is open-circuited is more difficult to locate if there are two or more parallels in each phase, because, obviously, a continuity test can only be applied to sections that are completely isolated and independent.

The growler, Fig. 151, can also be employed to locate an open-circuited coil. This may be done by successively short-circuiting individual coils spanned by the device as it is moved around the core; if a coil is intact, a spark will be observed as the shorted ends are quickly opened, while no spark will occur if a coil is open-circuited.

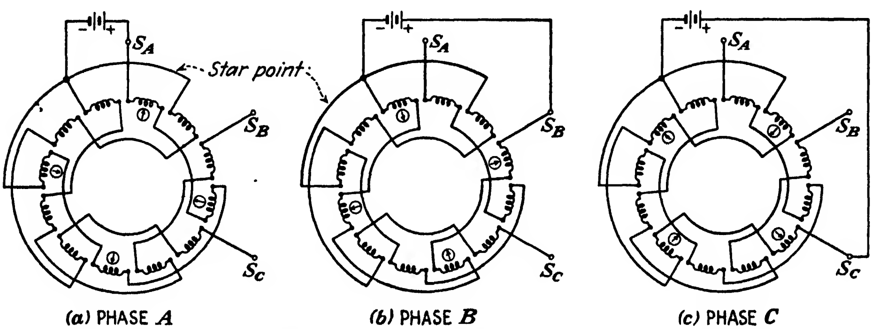


FIG. 153. Sketches illustrating how a 4-pole 3-phase star-connected winding is tested for the proper interphase labeling and connections.

Locating Incorrect Connections

The location of incorrect winding connections usually requires considerable patience, and the results of tests are often difficult to interpret. The simplest way to proceed is to employ a source of low-voltage direct current and a compass. The first step is to place the stator core and its winding, if that is what is being tested, on a test bench on end, *i.e.*, with extended coil ends vertical. The d-c supply, usually a dry cell or a storage battery, is next connected to each isolated phase in turn, and a small compass, with its face upward, is slowly moved around the inside circumference of the core. Careful note is then taken of whether the *north* end of the compass deflects toward or away from the core.

Assume that the winding is connected series-star and that it is desired to locate a reversed coil in one of the pole groups. With the d-c supply connected to one line terminal and the star point, *i.e.*, one of the phases, the compass is slowly moved from coil to coil. If there is no reversed coil in the phase, the *north* end will deflect in the same direction (*in*, for example) for all coils of each pole group and will reverse for successive pole groups. However, when the compass reaches a reversed coil, the compass

will show a tendency to reverse direction *within* the pole group. When the test upon the first phase has been completed, the d-c supply is shifted to the second and third phases, as the same procedure is repeated in each case.

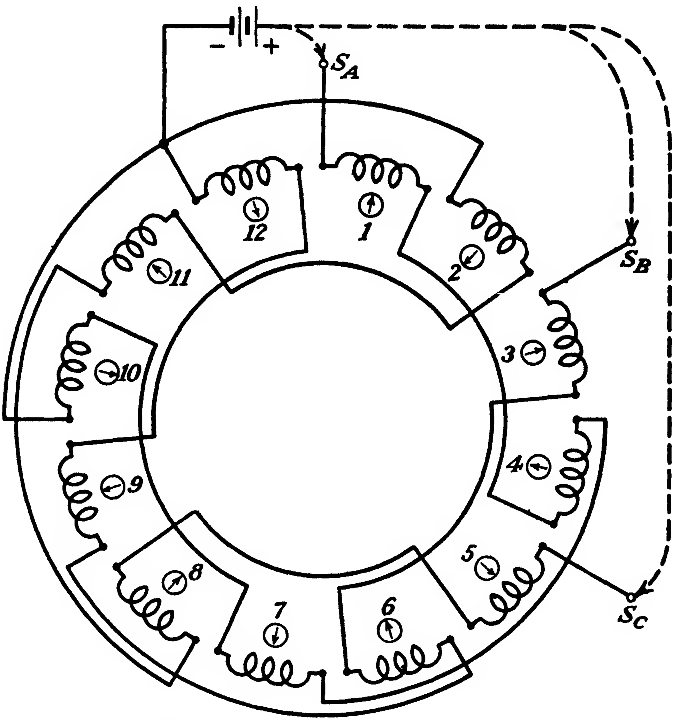


FIG. 154. Composite diagram showing magnetic polarities in a 4-pole 3-phase star-connected winding when tested for the proper interphase labeling. See Fig. 153 for the individual phase test results.

If a complete pole group in a phase is reversed, the compass needle will deflect in the same direction (*in*, for example) for three successive pole groups of the same phase.

To determine whether or not a complete phase is reversed in a three-phase winding, it is extremely important that the d-c source be applied successively with the correct polarities (+ and −) to the three phases. Assuming, as before, that the winding connection is series-star, arbitrarily connect the plus (+) terminal to one line lead, phase *A*, and the minus (−) terminal to the star point. Move the compass around the core in the usual way and observe the deflections; these are shown, in Fig. 153*a*, for a four-pole machine. Next, shift the plus (+) terminal to a second line lead, phase *B*, and repeat the compass test; the results are shown in Fig. 153*b*.

Finally shift the plus (+) terminal to the third line lead, phase C, and again observe the compass deflections; Fig. 153*c* indicates the needle directions. Now then, looking at all three diagrams simultaneously, it will be observed that *successive compass deflections reverse from pole group to pole group completely around the circumference if, and only if, the phases are properly interconnected.* This is better illustrated by Fig. 154, which is a composite diagram of the three sketches of Fig. 153. However, if one of the phases, phase C, for example, had been reversed, the compass deflections of pole groups 5, 8, 11, and 2 would have been reversed; under this condition the magnetic polarities would have reversed only after a succession of three similar deflections.

If the winding had been connected in delta, the same polarity tests would have been made only after the corners of the delta were opened. Then, for a correct succession of *north* and *south* poles, the three line leads S_A, S_B, and S_C would have been connected to the plus (+) terminal of the battery, and the three line leads F_A, F_B, and F_C would have been connected to the minus (−) battery terminal.

Summary

1. Because a-c induction-type machines do not generally have commutators, they are less likely to develop trouble than those designed for d-c service.

2. A-c machines sometimes develop trouble because: there is excessive heating due to overloads; ventilation is poor; squirrel-cage connections between rotor bars and end rings are loose; bearings are worn or are installed eccentrically; a motor is started and stopped frequently with excessive starting currents; objectionable surroundings, such as moisture, chemical fumes, dirt, etc., may exist; a machine may be operated on the wrong voltage or frequency; windings may be improperly connected.

3. Troubles in induction machines may be divided into two classes, namely, mechanical and electrical.

4. Several kinds of mechanical troubles are: loose bearings; misalignment of motor and load shafts; unbalanced rotors; loose bars in the rotor slots; eccentric or bent shafts; and others.

5. Electrical troubles may be classified as follows: grounds; short circuits; open circuits; poor connections between rotor bars and end rings; poor brush contacts on slip rings; low voltage; low frequency; unbalanced polyphase voltages; single-phasing of polyphase machines; incorrect winding connections.

6. A grounded winding may be responsible for a severe human shock if some part of the electrical system is grounded.

7. When a winding has two or more grounds, current can pass between the faults; the winding is then short-circuited as well as grounded.

8. Short-circuited windings cause currents to flow in local unconventional paths that heat the machine unduly.

9. To maintain service, it is sometimes necessary to disconnect a short-circuited coil from its pole group, connect around it, and cut the defective coil so that no current can flow through it.

10. Open circuits usually occur because of rough handling or careless soldering of connections.

11. Polyphase motors with open-circuited windings will not start.

12. Several kinds of improper winding connections may be made in the shop. These are: wrong pole grouping; reversing a coil within a pole group; reversing a complete pole group; reversing a complete phase.

13. Besides overheating and failure to start, motors, whose windings have failed or are improperly connected, may operate noisily.

14. When trouble is suspected, a machine should be disconnected from its load and examined carefully for mechanical defects first.

15. After a motor has been examined for possible physical faults, it should be operated at no load. While running, it should be inspected for noise, temperature rise, line currents, and other unusual evidences of trouble.

16. A ground test may be performed in various ways. These employ: a lamp circuit; a *megger;* a magneto; a special high-voltage transformer.

17. Short circuits may be located by feeling the winding for unusual temperature rise or by using a growler.

18. A growler is a commonly employed device that is essentially the primary of a transformer; the secondary is the motor winding when the device is properly placed in contact with the stator core.

19. Open-circuited coils may be located by the use of a growler, although a test-lamp circuit will generally be employed to determine which winding section is open.

20. The most common method for locating improper winding connections is to employ a source of low-voltage direct current and a compass.

Appendix

APPENDIX A

Natural Sines, Cosines, Tangents, and Cotangents

0° to 2°

	sin	cos	tan	cot	
0	.000000	1.00000	.00000	∞	90°
5′	1454	1.00000	145	687.55	55′
10′	2909	1.00000	291	343.77	50′
15′	4363	0.99999	436	229.18	45′
20′	5818	998	582	171.89	40′
25′	7272	997	727	137.51	35′
30′	.008727	996	.00873	114.59	30′
35′	.010181	995	.01018	98.218	25′
40′	1635	993	164	85.940	20′
45′	3090	991	309	76.390	15′
50′	4544	989	455	68.750	10′
55′	5998	987	600	62.499	5′
1°	.017452	.99985	.01746	57.290	89°
5′	.01891	982	.01891	52.882	55′
10′	.02036	979	.02036	49.104	50′
15′	181	976	182	45.829	45′
20′	327	973	328	42.964	40′
25′	472	969	473	40.436	35′
30′	618	966	619	38.188	30′
35′	763	962	764	36.178	25′
40′	.02908	958	.02910	34.368	20′
45′	.03054	953	.03055	32.730	15′
50′	199	949	201	31.242	10′
55′	345	944	346	29.882	5′
2°	.03490	.99939	.03492	28.636	88°
5′	635	934	638	27.490	55′
10′	781	929	783	26.432	50′
15′	.03926	923	.03929	25.452	45′
20′	.04071	917	.04075	24.542	40′
25′	217	911	220	23.695	35′
30′	362	905	366	22.904	30′
35′	507	898	512	22.164	25′
40′	653	892	658	21.470	20′
45′	798	885	803	20.819	15′
50′	.04943	878	949	20.206	10′
55′	.05088	870	..05095	19.627	5′
	cos	sin	cot	tan	

88° to 90°

3° to 8°

	sin	cos	tan	cot	
3°	.05234	.99863	.05241	19.081	87°
10′	524	847	533	18.075	50′
20′	.05814	831	.05824	17.169	40′
30′	.06105	813	.06116	16.350	30′
40′	395	795	408	15.605	20′
50′	685	776	700	14.924	10′
4°	.06976	.99756	.06993	14.301	86°
10′	.07266	736	.07285	13.727	50′
20′	556	714	578	13.197	40′
30′	.07846	692	.07870	12.706	30
40′	.08136	668	.08163	12.251	20′
50′	426	644	456	11.826	10′
5°	.08716	.99619	.08749	11.430	85°
10′	.09005	.99594	.09042	11.059	50′
20′	295	567	335	10.712	40′
30′	.0585	540	629	.385	30′
40′	.9874	511	.09923	10.078	20′
50′	.10164	482	.10216	9.7882	10′
6°	.10453	.99452	.10510	9.5144	84°
10′	.10742	421	.10805	.2553	50′
20′	.11031	390	.11099	9.0098	40′
30′	320	357	394	8.7769	30′
40′	609	324	688	.5555	20′
50′	.11898	290	.11983	.3450	10′
7°	.12187	.99255	.12278	8.1443	83°
10′	476	219	574	7.9530	50′
20′	.12764	182	.12869	.7704	40′
30′	.13053	144	.13165	.5958	30′
40′	341	106	461	.4287	20′
50′	629	067	.13758	.2687	10′
8°	.13917	.99027	.14054	7.1154	82°
10′	.14205	.98986	351	6.9682	50′
20′	493	944	648	.8269	40′
30′	.14781	902	.14945	.6912	30′
40′	.15069	858	.15243	.5606	20′
50′	356	814	540	.4348	10′
	cos	sin	cot	tan	

82° to 87°

Natural Sines, Cosines, Tangents, and Cotangents. (*Continued*)

9° to 14°

	sin	cos	tan	cot	
9°	.15643	.98769	.15838	6.3138	**81°**
10′	.15931	723	.16137	.1970	50′
20′	.16218	676	435	6.0844	40′
30′	505	629	.16734	5.9758	30′
40′	.16792	580	.17033	.8708	20′
50′	.17078	531	333	.7694	10′
10°	.17365	.98481	.17633	5.6713	**80°**
10′	651	430	.17933	.5764	50′
20′	.17937	378	.18233	.4845	40′
30′	.18224	325	534	.3955	30′
40′	509	272	.18835	3093	20′
50′	.18795	218	.19136	2257	10′
11°	.19081	.98163	.19438	5.1446	**79°**
10′	366	107	.19740	5.0658	50′
20′	652	.98050	.20042	4.9894	40′
30′	.19937	.97992	345	.9152	30′
40′	.20222	934	648	.8430	20′
50′	507	875	.20952	.7729	10′
12°	.20791	.97815	.21256	4.7046	**78°**
10′	.21076	754	560	.6382	50′
20′	360	692	21864	.5736	40′
30′	644	630	.22169	.5107	30′
40′	.21928	566	475	.4494	20′
50′	.22212	502	.22781	.3897	10′
13°	.22495	.97437	.23087	4.3315	**77°**
10′	.22778	371	393	.2747	50′
20′	.23062	304	.23700	.2193	40′
30′	345	237	.24008	.1653	30′
40′	627	169	316	.1126	20′
50′	.23910	100	624	.0611	10′
14°	.24192	.97030	.24933	4.0108	**76°**
10′	474	.96959	.25242	3.9617	50′
20′	.24756	887	552	.9136	40′
30′	.25038	815	.25862	.8667	30′
20′	320	742	.26172	.8208	20′
50′	601	667	483	.7760	10′
	cos	sin	cot	tan	

76° to 81°

15° to 20°

	sin	cos	tan	cot	
15°	.25882	.96593	.26795	3.7321	**75°**
10′	.26163	517	.27107	.6891	50′
20′	443	440	419	.6470	40′
30′	.26724	363	.27732	.6059	30′
40′	.27004	285	.28046	.5656	20′
50′	284	206	360	.5261	10′
16°	.27564	.96126	.28675	3.4874	**74°**
10′	.27843	.96046	.28990	.4475	50′
20′	.28123	.95964	.29305	.4124	40′
30′	402	882	621	.3759	30′
40′	680	799	.29938	.3402	20′
50′	.28959	715	.30255	.3052	10′
17°	.29237	.95630	.30573	3.2709	**73°**
10′	515	545	30891	.2371	50′
20′	.29793	459	.31210	.2041	40′
30′	.30071	372	530	.1716	30′
40′	348	284	.31850	.1397	20′
50′	625	195	.32171	.1084	10′
18°	.30902	.95106	.32492	3.0777	**72°**
10′	.31178	.95015	.32814	.0475	50′
20′	454	.94924	.33136	3.0178	40′
30′	.31730	832	460	2.9887	30′
40′	.32006	740	.33783	.9600	20′
50′	282	646	.34108	.9319	10′
19°	.32557	.94552	.34433	2.9042	**71°**
10′	.32832	457	.34758	.8770	50′
20′	.33106	361	.35085	.8502	40′
30′	381	264	412	.8239	30′
40′	655	167	.35740	.7980	20′
50′	.33929	.94068	.36068	.7725	10′
20°	.34202	.93969	.36397	2.7475	**70°**
10′	475	869	.36727	.7228	50′
20′	.34748	769	.37057	.6985	40′
30′	.35021	667	388	.6746	30′
40′	293	565	.37720	.6511	20′
50′	565	462	.38053	.6279	10′
	cos	sin	cot	tan	

70° to 75°

NATURAL SINES, COSINES, TANGENTS, AND COTANGENTS. (*Continued*)

21° to 26° | **27° to 33°**

	sin	cos	tan	cot			sin	cos	tan	cot	
21°	.35837	.93358	.38386	2.6051	**69°**	**27°**	.45399	.89101	.50953	1.9626	**63°**
10′	.36108	253	.38721	.5826	50′	10′	658	.88968	.51319	486	50′
20′	379	148	.39055	.5605	40′	20′	.45917	835	.51688	347	40′
30′	650	.93042	391	.5386	30′	30′	.46175	701	.52057	210	30′
40′	.36921	.92935	.39727	.5172	20′	40′	433	566	427	.9074	20′
50′	.37191	827	.40065	.4960	10′	50′	690	431	.52798	1.8940	10′
22°	.37461	.92718	.40403	2.4751	**68°**	**28°**	.46947	.88295	.53171	1.8807	**62°**
10′	730	609	.50741	.4545	50′	10′	.47204	158	545	676	50′
20′	.37999	499	.41081	.4342	40′	20′	460	.88020	.53920	546	40′
30′	.38268	388	421	.4142	30′	30′	716	.87882	54296	418	30′
40′	537	276	.41763	.3945	20′	40′	.47971	743	.54673	291	20′
50′	.38805	164	.42105	.3750	10′	50′	.48226	603	.55051	165	10′
23°	.39073	.92050	.42447	2.3559	**67°**	**29°**	.48481	.87462	.55431	1.8040	**61°**
10′	341	.91936	.42791	.3369	50′	10′	735	321	55812	1.7917	50′
20′	608	822	.43136	.3183	40′	20′	.48989	178	.56194	796	40′
30′	.39875	706	481	.2998	30′	30′	.49242	.87036	577	675	30′
40′	.40141	590	.43828	.2817	20′	40′	495	.86892	.56962	556	20′
50′	408	472	.44175	.2637	10′	50′	.49748	748	.57348	437	10′
24°	.40674	.91355	.44523	2.2460	**66°**	**30°**	.50000	86603	.57735	1 7321	**60°**
10′	.40939	236	.44872	.2286	50′	10′	252	457	58124	205	50′
20′	.41204	.91116	.45222	.2113	40′	20′	503	310	513	.7090	40′
30′	469	.90996	573	.1943	30′	30′	.50754	163	.58905	1.6977	30′
40′	734	875	.45924	.1775	20′	40′	.51004	.86015	59297	864	20′
50′	.41998	753	.46277	.1609	10′	50′	254	.85866	.59691	753	10′
25°	.42262	.90631	.46631	2.1445	**65°**	**31°**	.51504	.85717	.60086	1.6643	**59°**
10′	525	507	.46985	.1283	50′	10′	.51763	567	483	534	50′
20′	.42788	383	.47341	.1123	40′	20′	.52002	416	.60881	426	40′
30′	.43051	259	.47698	2.0965	30′	30′	250	264	.61280	319	30′
40′	313	133	.48055	809	20′	40′	498	.85112	.61681	212	20′
50′	575	.90007	414	655	10′	50′	745	.84959	.62083	107	10′
26°	.43837	.89879	.48773	2.0503	**64°**	**32°**	.52992	.84805	.62487	1.6003	**58°**
10′	.44098	752	.49134	353	50′	10′	.53238	650	.62892	1.5900	50′
20′	359	623	495	204	40′	20′	484	495	.63299	798	40′
30′	620	493	.49858	2.0057	30′	30′	730	339	.63707	697	30′
40′	.44880	363	.50222	1.9912	20′	40′	.53975	182	.64117	597	20′
50′	.45140	232	587	768	10′	50′	.54220	.84025	528	497	10′
	cos	sin	cot	tan			cos	sin	cot	tan	

64° to 69° | **58° to 63°**

NATURAL SINES, COSINES, TANGENTS, AND COTANGENTS. (*Continued*)

33° to 38° | **39° to 45°**

	sin	cos	tan	cot			sin	cos	tan	cot	′
33°	.54464	.83867	.64941	1.5399	**57°**	**39°**	.62932	.77715	.80978	1.2349	**51°**
10′	708	708	.65355	301	50′	10′	.63158	531	.81461	276	50′
20′	.54951	549	.65771	204	40′	20′	383	347	.81946	203	40′
30′	.55194	389	.66189	108	30′	30′	608	.77162	.82434	131	30′
40′	436	228	.66608	.5013	20′	40′	.63832	.76977	.82923	.2059	20′
50′	678	.83066	.67028	1.4919	10′	50′	.64056	791	.83415	1.1988	10′
34°	.55919	.82904	.67451	1.4826	**56°**	**40°**	.64279	.76604	.83910	1.1918	**50°**
10′	.56160	741	.67875	733	50′	10′	501	417	.84407	847	50′
20′	401	577	.68301	641	40′	20′	723	229	.84906	778	40′
30′	641	413	.68728	550	30′	30′	.64945	.76041	.85408	708	30′
40′	.56880	248	.69157	460	20′	40′	.65166	.75851	.85912	640	20′
50′	.57119	.82082	69588	370	10′	50′	386	661	.86419	571	10′
35°	.57358	.81915	70021	1.4281	**55°**	**41°**	.65606	.75471	.86929	1.1504	**49°**
10′	596	748	455	193	50′	10′	.65825	280	.87441	436	50′
20′	.57833	580	.70891	106	40′	20′	.66044	.75088	.87955	369	40′
30′	.58070	412	.71329	.4019	30′	30′	262	.74896	.88473	303	30′
40′	307	242	.71769	1.3934	20′	40′	480	703	.88992	237	20′
50′	543	.81072	.72211	848	10′	50′	697	509	.89515	171	10′
36°	.58779	.80902	.72654	1.3764	**54°**	**42°**	.66913	.74314	.90040	1.1106	**48°**
10′	.59014	730	.73100	680	50′	10′	.67129	.74120	.90569	1.1041	50′
20′	248	558	547	597	40′	20′	344	.73924	.91099	1.0977	40′
30′	482	386	.73996	514	30′	30′	559	728	.91633	913	30′
40′	716	212	.74447	432	20′	40′	773	531	.92170	850	20′
50′	.59949	.80038	.74900	351	10′	50′	.67987	333	.92709	786	10′
37°	.60182	.79864	.75355	1.3270	**53°**	**43°**	.68200	.73135	.93252	1.0724	**47°**
10′	414	688	.75812	190	50′	10′	412	.72937	.93707	661	50′
20′	645	512	.76272	111	40′	20′	624	737	.94345	599	40′
30′	.60876	335	.76733	.3032	30′	30′	.68835	537	.94896	538	30′
40′	.61107	.79158	.77196	1.2954	20′	40′	.69046	337	.95451	477	20′
50′	337	.78980	.77661	876	10′	50′	256	.72136	.96008	416	10′
38°	.61566	.78801	.78129	1.2799	**52°**	**44°**	.69466	.71934	.96569	1.0355	**46°**
10′	.61795	622	.78598	723	50′	10′	675	732	.97133	295	50′
20′	.62024	442	.79070	647	40′	20′	.69883	529	.97700	235	40′
30′	251	261	.79544	572	30′	30′	.70091	325	.98270	176	30′
40′	479	.78079	.80020	497	20′	40′	298	.71121	.98843	117	20′
50′	706	.77897	498	423	10′	50′	505	.70916	.99420	058	10′
						45°	.70711	.70711	1.00000	1.0000	**45°**
	cos	sin	cot	tan			cos	sin	cot	tan	

52° to 57° | **45° to 51°**

APPENDIX B

Wire Data

Round Wires—Standard Annealed Copper—American Wire Gauge

A.W.G. No.	Circular mils	Bare			Plain enamel					Formvar or formex				
		Diameter, mils	Resistance per 1,000 ft.		Diameter, mils	Turns per square inch	Feet per pound	Ohms per pound		Diameter, mils	Turns per square inch	Feet per pound	Ohms per pound	
			25°C.	75°C.				25°C.	75°C.				25°C.	75°C.
0000	211,600	460	0.050	0.060										
000	167,800	410	0.063	0.075										
00	133,100	365	0.079	0.094										
0	105,500	325	0.100	0.120										
1	83,690	289	0.126	0.150										
2	66,370	257	0.159	0.189										
3	52,640	229	0.202	0.240										
4	41,740	204	0.254	0.303										
5	33,100	182	0.319	0.381										
6	26,250	162	0.403	0.480	164	......	12.5	0.0050	0.0060	166	......	12.4	0.0049	0.0059
7	20,820	144	0.510	0.608	146	......	15.7	0.0079	0.0095	148	......	15.6	0.0078	0.0094
8	16,150	128	0.645	0.770	130	......	19.8	0.0125	0.0150	132	......	19.7	0.0124	0.0149
9	13,090	114	0.813	0.970	116	......	25.0	0.0198	0.0238	118	......	24.9	0.0197	0.0237
10	10,380	102	1.02	1.21	103	......	31.5	0.0315	0.0378	105	......	31.4	0.0314	0.0376
11	8,234	90.7	1.29	1.53	92.7	......	39.7	0.0501	0.0601	94.2	......	39.5	0.0498	0.0598
12	6,530	80.8	1.62	1.93	82.7	......	50.0	0.0796	0.0958	84.2	......	50.0	0.0794	0.0952

13	5,178	72.0	2.04	2.43	73.8	......	63.0	0.1265	0.1520	75.3	......	62.9	0.1260	0.1512
14	4,107	64.1	2.57	3.07	65.9	......	79.4	0.2012	0.2415	67.3	......	79.3	0.2005	0.2405
15	3,257	57.1	3.24	3.87	58.8	......	100	0.3197	0.3840	60.2	......	99.0	0.3152	0.378
16	2,583	50.8	4.10	4.89	52.4	358	126	0.5080	0.0610	53.8	340	125	0.5020	0.602
17	2,048	45.3	5.15	6.14	46.9	466	159	0.8086	0.970	48.2	425	158	0.8001	0.960
18	1,624	40.3	6.51	7.76	41.8	572	201	1.285	1.54	43.1	530	199	1.271	1.525
19	1,288	35.9	8.21	9.79	37.4	718	253	2.040	2.45	38.6	660	250	2.061	2.475
20	1,022	32.0	10.3	12.3	33.4	875	319	3.245	3.89	34.6	800	315	3.197	3.84
21	810	28.5	13.0	15.5	29.9	1,080	402	5.153	6.18	31.0	990	398	5.094	6.11
22	642	25.3	16.5	19.7	26.7	1,332	507	8.198	9.75	27.7	1,200	503	8.188	9.80
23	509	22.6	20.7	24.7	23.8	1,650	639	13.02	15.6	24.9	1,500	633	12.89	15.48
24	404	20.1	26.2	31.2	21.3	2,045	805	20.65	24.8	22.3	1,820	794	20.38	24.4
25	320	17.9	33.0	39.4	19.0	2,500	1,010	32.84	39.4	20.0	2,200	1,000	32.37	38.8
26	254	15.9	41.8	49.9	17.0	3,090	1,280	52.14	62.5	17.9	2,700	1,260	51.42	61.7
27	201	14.2	51.4	62.5	15.2	3,806	1,610	83.11	99.5	16.1	3,300	1,580	81.32	97.5
28	160	12.6	66.6	79.4	13.6	4,670	2,030	131.6	157.5	14.4	4,000	2,000	129.8	156
29	127	11.3	82.8	98.7	12.2	5,640	2,550	209.2	251	13.0	4,700	2,520	206.2	247
30	100	10.0	106	126	10.8	6,860	3,220	332.4	399	11.6	5,500	3,160	326.1	391
31	79.7	8.9	134	159	9.7	8,320	4,050	528.2	633	10.4	6,500	3,990	519	623
32	63.2	8.0	165	197	8.8	10,060	5,120	839.3	1,010	9.4	7,700	5,050	829	995
33	50.1	7.1	210	250	7.8	11,956	6,430	1,395	1,600	8.4	9,000	6,330	1,310	1,570
34	39.8	6.3	266	318	6.9	14,250	8,160	2,124	2,550	7.5	10,500	7,940	2,071	2,485
35	31.5	5.6	337	402	6.1	16,940	10,200	3,364	4,140	6.7	12,500	10,050	3,306	3,970
36	25	5.0	423	504	5.5	20,000	12,850	5,347	6,410	6.0	14,900	12,650	5,247	6,300

ROUND AND SQUARE DOUBLE-COTTON-COVERED ANNEALED COPPER WIRES

A.W.G. No.	Diameter, mils		Round d.c.c.							Square d.c.c.						
			Circular mils	Feet per pound	Turns per square inch	Resistance				Circular mils	Feet per lb.	Turns per sq. inch	Resistance			
						1,000 ft.		Pound					1,000 ft.		Pound	
	Bare	Insul.				25°C.	75°C.	25°C.	75°C.				25°C.	75°C.	25°C.	75°C.
1	289	307	83,690	3.79	10.9	0.126	0.150	0.00048	0.00057	102,216	3.20	10.2	0.103	0.123	0.00033	0.00040
2	257	276	66,370	4.78	13.5	0.159	0.189	0.00076	0.00091	80,164	4.07	12.6	0.130	0.156	0.00053	0.00064
3	229	247	52,640	6.04	17.0	0.202	0.240	0.00122	0.00146	62,670	5.21	15.9	0.169	0.203	0.00088	0.00105
4	204	221	41,740	7.63	21.2	0.254	0.303	0.00193	0.00232	50,729	6.42	19.8	0.207	0.248	0.00133	0.00160
5	182	198	33,100	9.66	25.8	0.319	0.381	0.00308	0.00370	39,729	8.19	24.6	0.266	0.319	0.00218	0.00262
6	162	177	26,250	12.0	32.8	0.403	0.480	0.00495	0.00582	32,371	10.05	30.8	0.327	0.393	0.00328	0.00393
7	144	159	20,820	15.1	40.6	0.510	0.608	0.00770	0.00923	25,475	12.76	38.2	0.415	0.498	0.0053	0.00635
8	128	142	16,150	19.0	50.2	0.645	0.770	0.0123	0.0147	19,970	16.23	47.8	0.530	0.636	0.0086	0.01032
9	114	125	13,090	24.0	64.5	0.813	0.970	0.0195	0.0236	15,616	20.67	61.7	0.680	0.815	0.0140	0.0168
10	102	112	10,380	30.4	82.1	1.02	1.21	0.0310	0.0372	12,532	25.7	77.0	0.840	1.01	0.0216	0.0260
11	90.7	99.5	8,234	38.5	102	1.29	1.53	0.0485	0.0581	9,800	32.8	98.0	1.08	1.30	0.0354	0.0425
12	80.8	89.6	6,530	48.8	125	1.62	1.93	0.079	0.095	7,630	42.2	119	1.38	1.65	0.0583	0.0700
13	72.0	80.7	5,178	61.6	153	2.04	2.43	0.126	0.151	5,909	54.3	148	1.79	2.15	0.0970	0.1163
14	64.1	72.8	4,107	77.7	196	2.57	3.07	0.199	0.239	4,545	70.2	182	2.32	2.78	0.1630	0.1635
15	57.1	65.9	3,257	91.0	237	3.24	3.87	0.295	0.354							

16	50 8	59 6	2,583	122	278	4 10	4 89	0 500	0 600							
17	45 3	54 1	2,048	150	345	5 15	6 14	0 773	0 925							
18	40 3	49 1	1,624	189	440	6 51	7 76	1 23	1 47							
19	35 9	44 7	1,288	237	510	8 21	9 79	1 94	2 33							
20	32 0	40 8	1,022	298	601	10 3	12 3	3 07	3 68							
21	28 5	37 3	810	370	710	13 0	15 5	4 81	5 76							
22	25 3	33 6	642	461	845	16 5	19 7	7 62	9 13							
23	22 6	30 9	510	584	995	20 7	24 7	12 1	14 6							
24	20 1	28 4	404	745	1,175	26 2	31 2	19 5	23 4							
25	17 9	25 7	320	903	1,370	33 0	39 4	30 0	36 0							
26	15 9	23 8	254	1,118	1,590	41 8	49 9	46 6	45 9							
27	14 2	22 0	201	1,422	1,835	52 4	62 5	74 5	88 2							
28	12 6	20 5	160	1,758	2,130	66 6	79 4	111 7	134							
29	11 3	19 1	127	2,207	2,430	82 8	98 7	183	220							
30	10 0	17 8	100	2 534	2,730	106	126	268	321							
31	8 9	16 7	79 7	3,160	3,090	134	159	405	486							
32	8 0	15 8	63 2	3,910	3,390	165	197	631	756							
33	7 1	14 9	50 1	4,640	3,820	210	250	940	1,128							
34	6 3	14 1	39 7	5,470	4,180	266	318	1,405	1,685							
35	5 6	13 4	31 5	6,360	4,590	337	402	2,050	2,460							
36	5 0	12 4	25 0	7,310	4,950	423	504	3,000	3,600							

Rectangular Annealed Copper Wires—Circular Mils (within 3 per cent accuracy)

Size	0.045	0.050	0.055	0.065	0.075	0.085	0.095	0.105	0.115	0.125	0.135	0.145	0.155	0.165
0.060	2,890	3,210	3,460	4,290	5,000	5,750	6,430	7,170	7,920	8,700	9,470	10,200	10,900	11,700
0.070	3,400	3,820	4,230	5,050	5,930	6,780	7,640	8,510	9,400	10,250	11,150	12,080	12,900	13,850
0.080	3,920	4,400	4,880	5,820	6,820	7,800	8,800	9,800	10,860	11,800	12,850	13,900	15,000	16,000
0.090	4,500	5,000	5,540	6,660	7,750	8,850	10,000	11,150	12,320	13,500	14,700	15,780	16,850	18,100
0.100	5,000	5,600	6,210	7,400	8,700	9,930	11,200	12,500	13,800	15,100	16,320	17,700	18,900	20,150
0.110	5,540	6,210	6,880	8,280	9,650	11,020	12,420	13,850	15,300	16,650	18,150	19,450	20,800	22,150
0.120	6,100	6,820	7,580	9,030	10,530	12,120	13,700	15,200	16,850	18,300	19,800	21,250	22,700	24,200
0.130	6,650	7,400	8,820	9,880	11,500	13,250	14,920	16,500	18,250	19,800	21,400	23,000	24,600	26,200
0.140	7,160	8,040	8,900	10,720	12,500	14,300	16,100	17,950	19,650	21,400	23,100	24,800	26,500	28,300
0.150	7,750	8,700	9,650	11,500	13,500	15,400	17,380	19,250	21,000	22,900	24,800	26,600	28,400	30,300
0.160	8,350	9,250	10,300	12,400	14,400	16,450	18,550	20,500	22,450	24,400	26,500	28,400	30,300	32,400
0.170	8,870	9,930	11,020	13,250	15,400	17,620	19,700	21,800	23,900	26,200	28,200	30,200	32,300	34,400
0.180	9,460	10,530	11,680	14,030	16,330	18,650	20,900	23,100	25,400	27,600	29,900	32,000	34,200	36,500
0.190	10,000	11,200	12,420	14,900	17,350	19,700	22,000	24,350	26,900	29,200	21,600	33,800	36,100	38,500
0.200	10,530	11,800	13,100	15,720	18,300	20,750	23,200	25,800	28,300	30,700	33,300	35,600	38,000	40,600
0.210	11,120	12,500	13,860	16,500	19,200	21,750	24,350	27,100	29,700	32,250	35,000	37,400	39,900	42,600
0.220	11,680	13,100	14,630	17,450	20,100	22,800	25,700	28,400	31,100	33,800	36,700	39,200	41,900	44,600
0.230	12,300	13,800	15,280	18,250	21,052	23,830	26,900	29,700	32,500	35,300	38,400	40,000	43,800	46,700

0.240	12,850	14,400	16,000	19,050	22,000	25,150	28,000	31,000	34,000	37,000	40,000	42,900	45,800	48,700
0.250	13,500	15,100	16,630	19,800	22,900	26,200	29,200	32,300	35,300	38,500	41,600	44,700	47,700	50,800
0.260	14,030	15,720	17,450	20,600	23,800	27,200	30,400	33,600	36,700	40,000	43,300	46,500	49,600	52,800
0.270	14,700	16,330	18,130	21,400	24,900	28,200	31,600	34,900	38,200	41,500	44,900	48,300	51,500	54,800
0 280	15,220	16,940	18,800	22,500	25,810	29,300	32,700	36,200	39,600	43,000	46,600	50,100	53,400	56,900
0.290	15,750	17,700	19,450	23,000	26,750	30,300	33,900	37,400	41,000	44,500	48,200	51,900	55,300	58,900
0.300	16,330	18,300	20,100	23,800	27,650	31,400	35,000	38,700	42,400	46,100	49,900	53,700	57,200	61,100
0.310	16,850	18,900	20,800	24,800	28,600	32,400	36,200	40,000	43,800	47,600	51,500	55,500	59,100	63,300
0.320	17,580	19,500	21,450	25,600	29,500	33,400	37,300	41,300	45,200	49,200	53,200	57,300	61,000	65,500
0.330	18,130	20,100	22,150	26,400	30,450	34,500	38,500	42,600	46,600	50,700	54,800	59,000	63,400	67,500
0.340	18,700	20,700	22,800	27,200	31,400	35,500	39,600	43,900	48,000	52,200	56,500	60,700	65,200	69,500
0.350	19,200	21,300	23,500	28,000	32,300	36,500	40,800	45,200	49,500	53,800	58,100	62,800	67,200	71,500
0.360	19,750	21,900	24,150	28,800	33,200	37,600	41,900	46,500	50,900	55,300	59,700	64,700	69,000	73,600
0.370	20,300	22,500	25,000	29,600	34,100	38,600	43,100	47,800	52,300	56,800	61,300	66,500	71,000	75,600
0.380	20,800	23,100	25,700	30,400	35,000	39,700	44,200	49,100	53,700	58,300	62,900	68,300	73,000	77,700
0.390	21,400	23,700	26,400	31,200	35,900	40,700	45,400	50,400	55,100	59,900	65,100	70,200	75,800	79,700
0.400	22,000	24,200	27,100	32,100	36,750	41,800	46,600	51,600	56,500	61,500	67,000	71,900	76,800	81,800

Index